

RESEARCH STUDY ON MULTI-KW DC DISTRIBUTION SYSTEM

FINAL REPORT

CONTRACT NAS8-30778

NOVEMBER 1975

BY

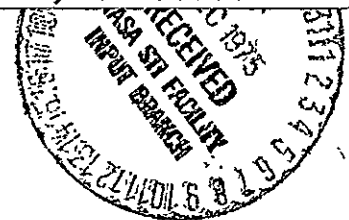
E. A. BERKERY

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Prepared for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Marshall Space Flight Center, Alabama

TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

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Among the TRW personnel who contributed to this program, R. Hannah and J. Clements of the Electromagnetic Compatibility Department provided the analysis of spacecraft noise data and simulation of power distribution cable. A. Krausz reviewed all reports and provided effective constructive criticism.

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1.0 INTRODUCTION

1.1 BACKGROUND

This report summarizes the results of work performed during the extended period of performance on contract NAS8-39778. The design and study effort for the basic contract was presented in an earlier report (Research Study on Multi-KW DC Distribution System, May 1975, Final Report).

This program was planned on the basis of recommendations resulting from a comprehensive "Space Vehicle Electrical Power Processing Distribution and Control Study", (NAS8-26270) performed by TRW Systems as part of the NASA Space Vehicle Technology Development Program. The objectives of the first year of this program "Multi-KW DC Distribution System Study" (NAS8-28726) were:

- Provide detailed definition of the program and test objectives
- Make recommendations for selection and sizing of subsystem equipment
- Evaluate high voltage dc power distribution system state-of-art and availability of test hardware.

This study was completed successfully April 1974. The objective of the second year of effort was to provide sufficiently detailed definitions of subsystems to enable planning and initial installation of test laboratory equipment by Marshall Space Flight Center personnel. The subsequent phases of this program provide support for procurement and installation of hardware, system test planning and evaluation.

1.2 SCOPE OF WORK

The current phase of the Power Distribution and Control Development Program is a continuation of the TRW and MSFC joint effort and consists of:

- Study and analysis of expected noise characteristics and sources
- Simulation of transient effects of long power distribution cables
- Provide design and update configurations to meet evolving requirements.
- Provide support to MSFC in-house assembly and installation efforts

TRW Systems efforts are limited to design analysis and trade-off studies; procurement, fabrication and installation of equipment for the technology breadboard are performed by NASA/MSFC.

2.0 SUMMARY AND CONCLUSION

2.1 PROGRAM OBJECTIVES

The primary objective of the Multi-KW Distribution System Technology Program is to evaluate and demonstrate the performance of power subsystems at distribution voltages up to 300V. The test article is to be designed to simulate a power distribution system for large aerospace vehicles. The equipment is to be configured to provide sufficient access to allow detailed evaluation of subsystem performance and characteristics in a realistic electrical environment. Cost is minimized by selection of industrial quality components and extensive use of model shop approaches. The basic elements of the test facility are illustrated in Figure 2.1-1 and consist of the power source, conventional and digital supervision and control equipment, power distribution harness and simulated loads. The regulated DC power supplies provide steady-state power up to 36 KW at 120 VDC. Power for simulated line faults will be obtained from two banks of 90 ampere-hour lead-acid batteries. The relative merits of conventional and multiplexed power control will be demonstrated by the Supervision and Monitor Unit (SMU) and the Automatically Controlled Electrical Systems (ACES) hardware. The distribution harness is supported by a metal duct which is bonded to all component structures and functions as the system ground plane. The Load Banks contain passive resistance and reactance loads, solid state power controllers and active pulse width modulated loads.

The objectives of this phase of the program are:

- (1) Establish a preliminary estimate of power distribution system noise and transient stress on switchgear in large space vehicle power systems.
- (2) Provide design support for MSFC procurement, assembly and installation activities.

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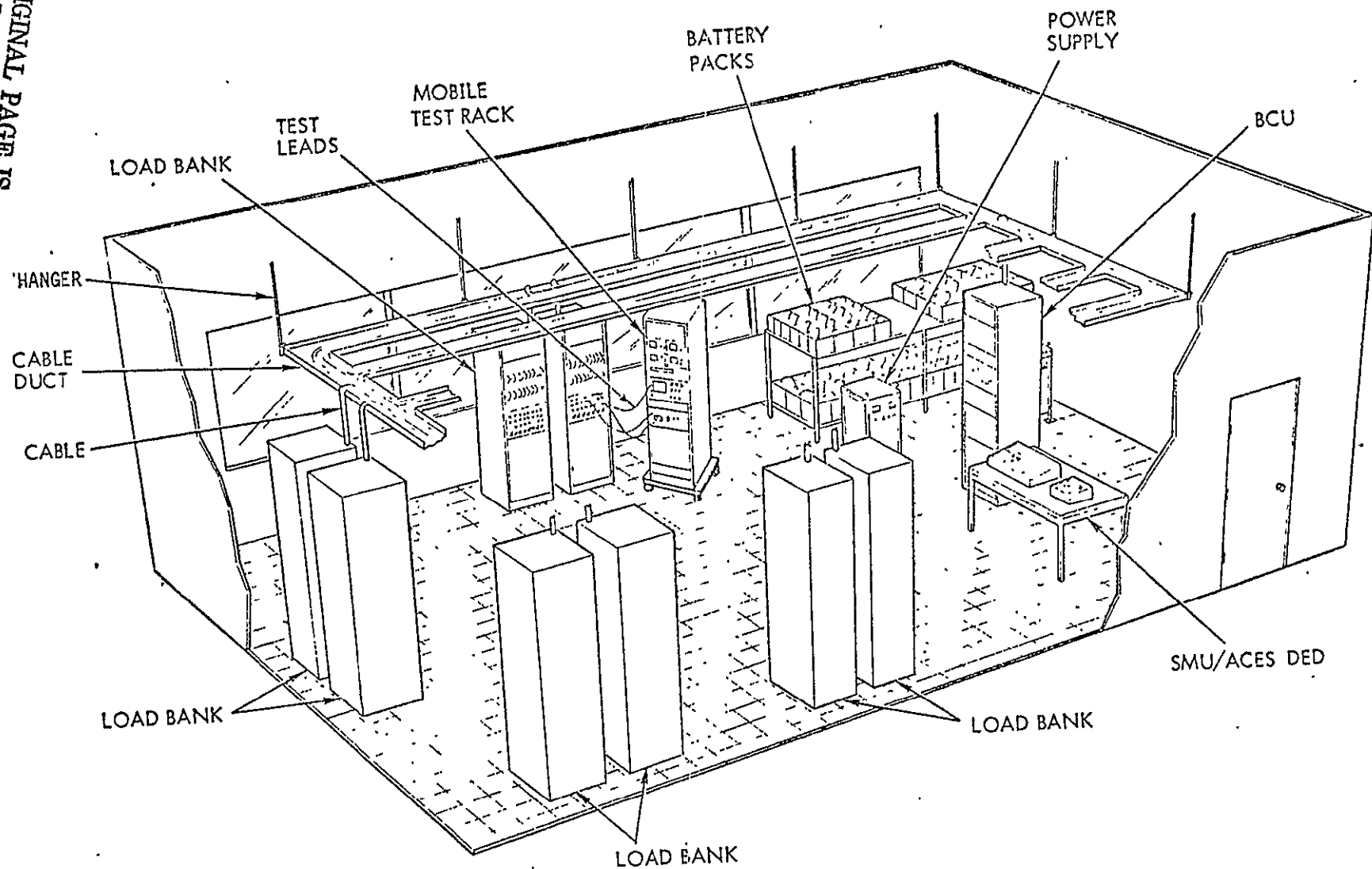


Figure 2.1-1. High Voltage DC Laboratory

The intent of the noise analysis was to evaluate the effect of flight designs of long power distribution cables on load interface EMI requirements. The analysis of the characteristic transient stress on solid state RPC's (Remote Power Controllers) was a specific requirement of this study.

The TRW in-house support effort defined during this study period consisted primarily of an update of the BCU design and revision of interface definitions.

2.2 PROGRAM ACCOMPLISHMENTS

The Power Distribution Noise Study (Section 3.2) consisted of a review of available data, cable simulation and analysis. The data survey involved a literature search as well as direct inquiry at several NASA and military technical centers. Within the limitations of this study it was established that there were no available data which characterized the noise on a large DC power distribution system of aerospace quality. The study did not exhaust potential data sources, however, and it is expected that some additional investigations will be performed in this area in subsequent phases of this program. Significant study and analysis of cable noise and transient propagation have been performed with respect to large ground power systems. Although the results of commercial power system studies are not applicable here, the analytic techniques utilized provide a potential approach for the synthesis of EMI on large spacecraft power distribution systems.

A fifty meter (50m) cable pair was simulated to study interactions between the cable, load and power source terminations. Particular attention was directed toward evaluating stresses on solid state switchgear. The conclusions of this study indicate that the state-of-the-art semiconductor switches represent a viable approach toward the implementation of power system design with distribution voltages of 120 VDC or less.

The evaluation of power system noise characteristics was based on current spacecraft data obtained at TRW, interface hardware filter designs and power cable parameters. Parametric approaches were defined for evaluating switching transients at various distribution voltage levels. These analytic approaches will be utilized to correlate the results of test operations performed at MSFC.

The interface definition and design for the Bus Control Unit (Section 3.3) was updated to be consistent with the requirements and quality established during this contract. Drawings and specifications have been prepared and are included in this report.

3.0 DETAILED TECHNICAL DESCRIPTION

3.1 INTRODUCTION

The purpose of the Multi-KW Distribution System Study and associated NASA/MSFC in-house effort is to demonstrate technology readiness and performance advantages of high voltage dc (HVDC) distribution and control systems for large manned aerospace vehicles. This demonstration is to be accomplished through operation and test of a technology breadboard which simulates an advanced design power system and includes power source, distribution, loads, supervision and control functions. The continued development of solid state power controllers provides additional impetus to the interest in high voltage distribution systems. These devices are currently gaining acceptance for space applications and can provide a solution to high voltage power switching problems. It is planned to include several solid state remote power controllers in the technology breadboard to demonstrate their performance and compatibility with the power distribution system.

The integration of an electrical system which is comprised of many complex subsystems designed and assembled at remote locations is based on interface documentation which is necessarily limited. The electromagnetic compatibility problem increases with the physical size and power handling capability of the system due to increased numbers of functions, greater opportunity for random interactions and the higher level of energy storage in the distribution cables and load filters. The application of solid state switchgear requires establishment of a basis for the prediction of electrical stress during integrated system operation. Low frequency EMI and transients for which the distribution cable may be represented as a simple lumped constant network are predictable by classic circuit analysis. The evaluation of fast transients and high frequency signals must allow for the effect of distributed cable constants. Abrupt changes in load current or source voltage require change of energy states in the distribution cable and are accompanied by high amplitude transients and ringing effects. Although mathematical approaches to this phenomenon are available, it was decided that simulation techniques were consistent with the time and cost constraints of this study program. The evaluation of transients due to interaction between the cable and a solid state switch is presented in Section 3.2 of this report.

The detailed design of the power distribution breadboard was initiated in Contract NAS8-28726. This contract effort provided the definition of the test breadboard elements (Figure 3.1-1) and the design of the Bus Control Unit (BCU). The design of the balance of the components was provided during the initial phase of the current contract. In order to maintain a consistent level of detail and clarify interface definitions it was necessary to provide a through update of the BCU design. The revised design is presented in Section 3.3. of this report.

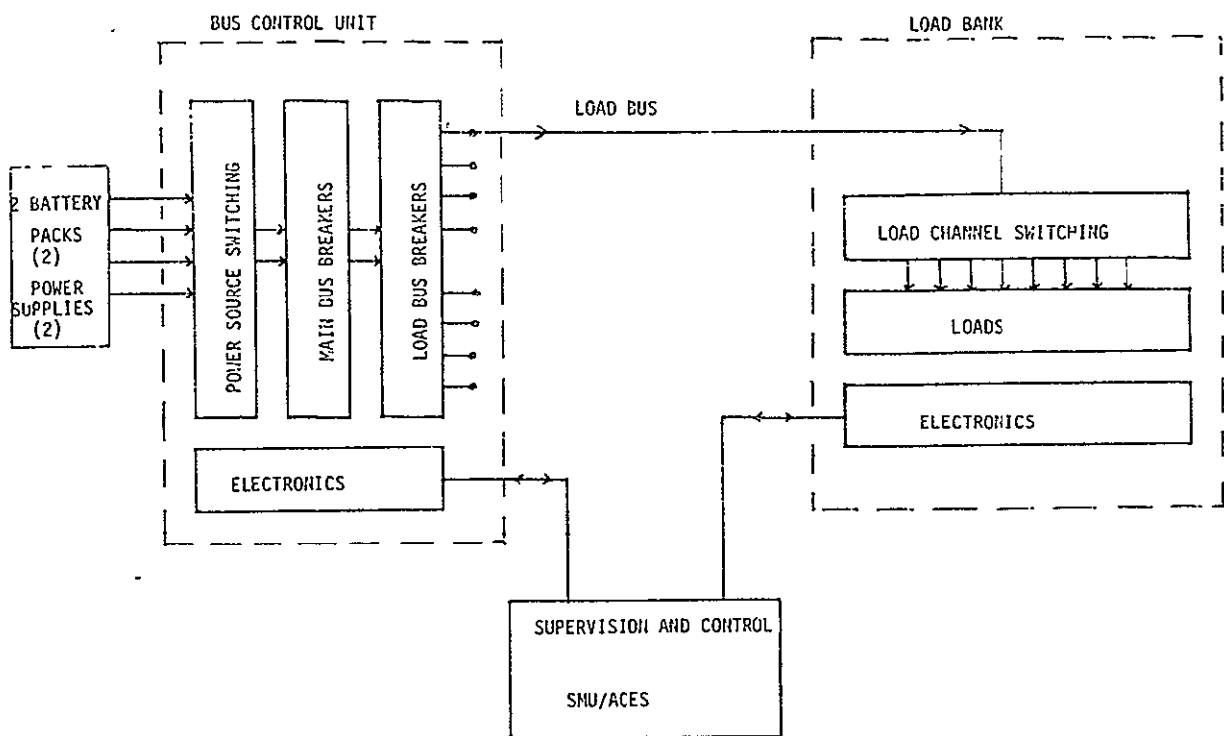


Figure 3.1-1. Functional Block Diagram ~ Test Facility

3.2 POWER DISTRIBUTION CABLE NOISE

A study was performed of the effect of high voltage direct-current (HVDC) power on electromagnetic compatibility (EMC) requirements. Measured data on current spacecraft (28VDC) power systems were analysed in an attempt to establish a basis for prediction of noise on HVDC systems. A cable model with distributed constants was developed to simulate performance of long cables and to verify predictions of fast switching transients. The results of these studies and analysis are presented in subsequent paragraphs.

3.2.1 Survey of Spacecraft Power Quality

Measured characteristics of existing designs were utilized to study power system distribution noise. Primary bus power quality data have been obtained for typical low earth and synchronous orbit spacecraft. In both cases, the primary power is supplied by a combination of solar array and re-chargeable batteries which deliver maximum required loads of several hundred watts at a primary bus voltage of +28VDC. Bus impedance is generally less than a few tenths of an ohm at frequencies below 100 KHz, as shown by the representative data of Figure 3.2.1-1, and single point grounding of primary power is utilized.

Measurement of power quality is performed during system integration and test. The principal test point was established at the output of the power control unit (PCU), where junction, or "breakout," boxes are inserted in the primary power line to facilitate connection of test instrumentation. Observations of bus power quality are made as the system is cycled through the events occurring during simulation of various spacecraft operational modes (boost phase, acquisition, deployment, eclipse, on-station, etc.). Transient generated interference is monitored using oscilloscopes or memory volt-meters in conjunction with a visicorder, while the steady-state noise spectrum is analyzed with calibrated automatically tuned narrowband receivers and X-Y plotters.

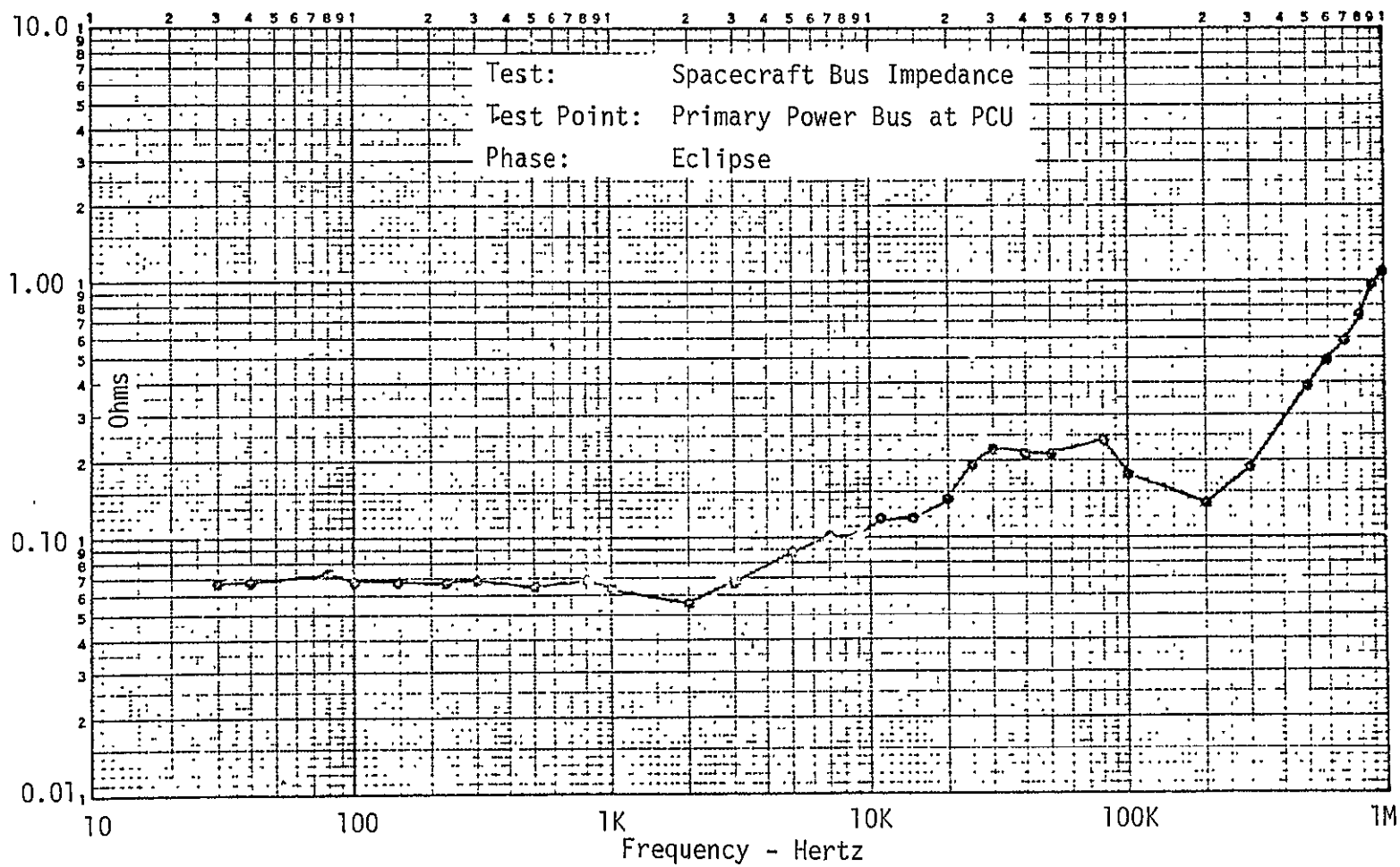


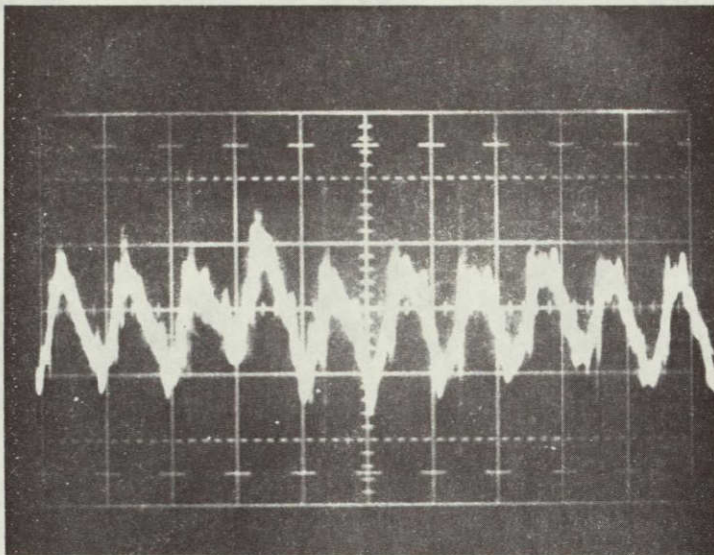
Figure 3.2.1-1. Typical Spacecraft Primary Bus Impedance

The dominant features of the noise observed on the 28 VDC bus are single event switching transients and steady-state ripple or noise spikes occurring at converter switching frequencies. In some instances additional low frequency beat tones or high frequency narrowband signals (probably cross-coupled from nearby signal or RF circuits) can also be seen.

The composite steady-state converter noise on the primary power bus ranges in amplitude from 40 mV to 80 mV p-p for these systems. Oscilloscope photographs of typical signals are presented in Figures 3.2.1-2 and 3.2.1-3, which show 20 kHz converter switching noise signals, amplitude modulated by lower frequency (~ 300 Hz) beat signals. The spectral content of the signal depicted in Figure 3.2.1-2, as obtained with a narrowband receiver, is shown in Figure 3.2.1-4. Using typical values of bus impedance, the 20 kHz fundamental component of this signal yields a ripple current of approximately 50 ma peak.

Single event transients due to load switching, displaying durations of 1 msec to 100 msec and amplitudes of ± 0.5 volts to ± 5.0 volts, were found to be typical of 28 VDC power systems. These amplitudes are indicative of load converter peak inrush currents of up to 30 amps for heavy loads such as communications transmitters and TWTAs. Ordnance firing generally produced peak bus transients of 0.5 volts or less.

Both single event load switching transients and converter steady-state switching noise, as observed on the primary power bus, are directly related to the nominal load current. It is to be expected, therefore, that for comparable impedance and load power requirements, these types of conducted electromagnetic interference will be significantly less in the high voltage DC system than in its +28 VDC counterpart. This may in turn pave the way for relaxed EMI filtering requirements, with an attendant savings in weight, as pointed out in previous studies (see Reference 1). Additionally, coupling of power line conducted interference to sensitive analog or digital circuits, which at low frequencies occurs predominantly via mutual inductance, will be reduced by the lower currents in the HVDC system.

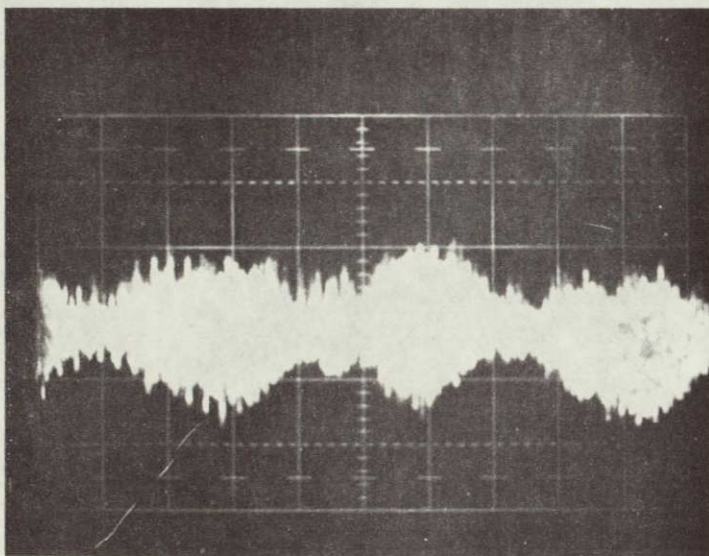


Test Point: Pri Pwr Bus
Steady-State

Oscilloscope Settings:

Amplitude 20 mv/cm
 Time 50 μ s/cm

Amplitude = 40 mV p-p
 (Switching Transient
 Amplitude)



Test Point: Pri Pwr Bus
Steady-State

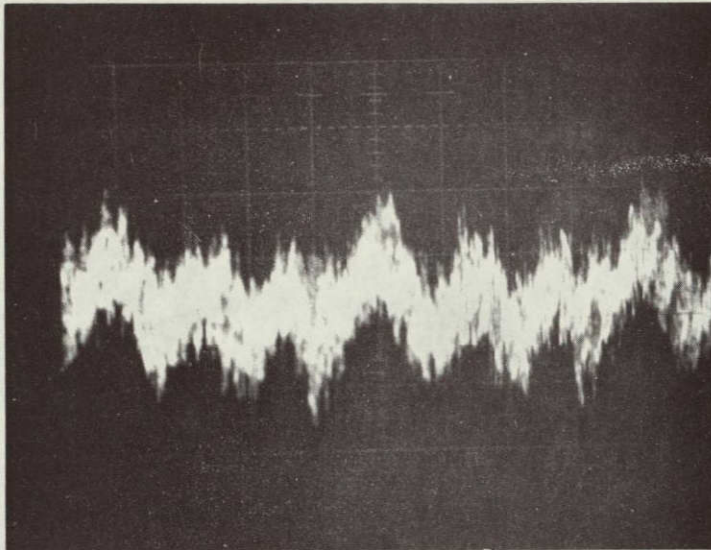
Oscilloscope Settings:

Amplitude 20 mv/cm
 Time 1 ms/cm

Modulation $f = 0.31$ kHz
 (Due to Frequency Beat)

Amplitude = 16 mV p-p

Figure 3.2.1-2. EMC Qualification S/C Test Data
 (On-Station Mode)



Test Point: Pri Pwr Bus
PCU Output

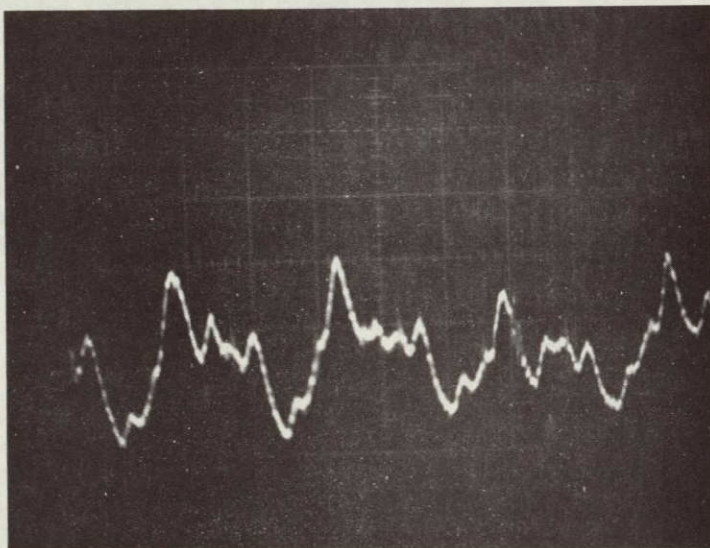
Oscilloscope Settings:
20 mv/cm, 2 ms/cm

SS Signal Characteristics

Amplitude: V-pk

Duration : S

Remarks:



Test Point: Pri Pwr Bus
PCU Output

Oscilloscope Settings:
20 mv/cm, 20 μ s/cm

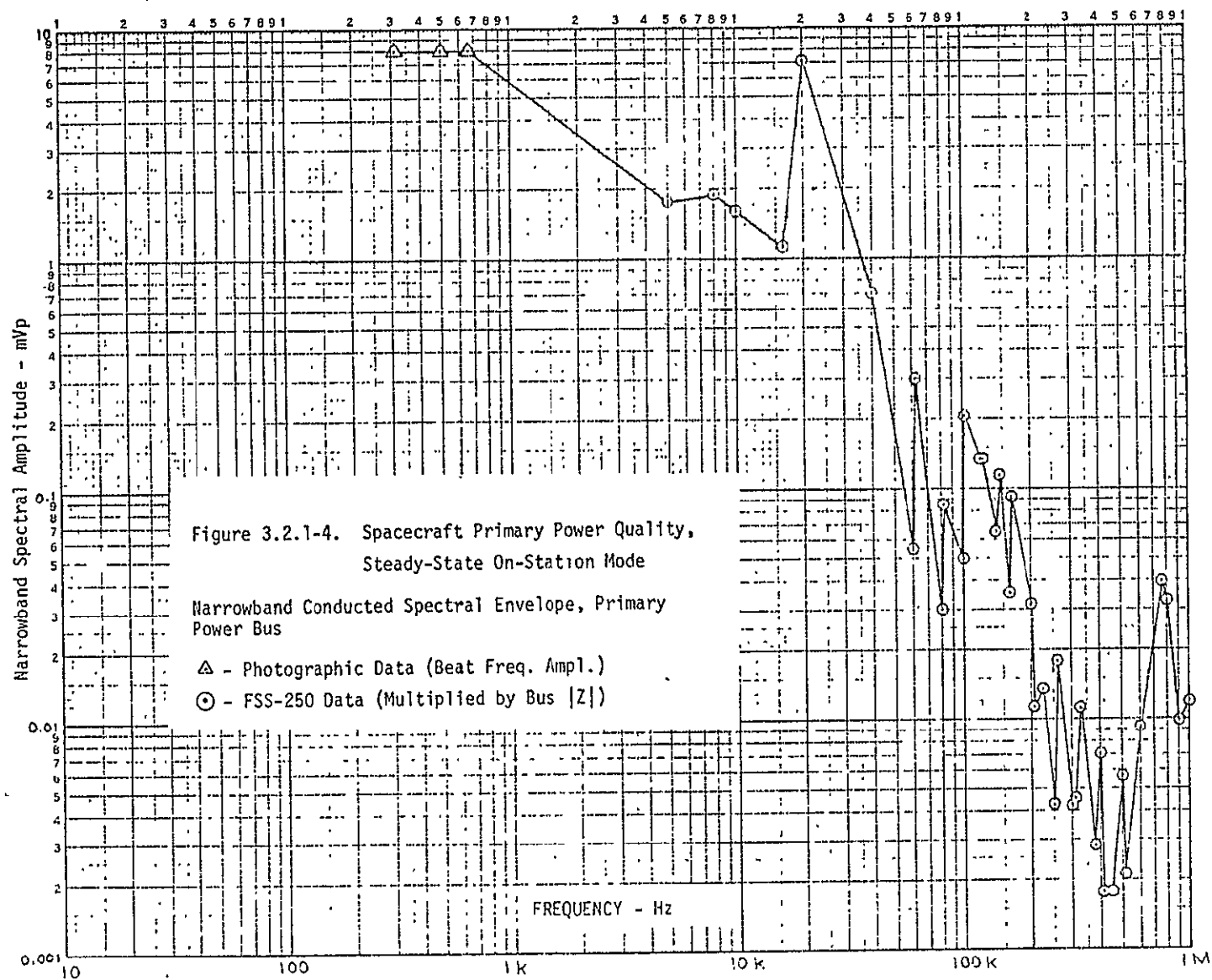
SS Signal Characteristics

Amplitude: V-pk

Duration : S

Remarks:

Figure 3.2.1-3. EMC Qualification S/C Test Data
 (On-Orbit Mode)



3.2.2 Transient Analysis

In the following paragraphs, the technique for investigating the transient behavior of 120 VDC power systems using long (50 meter) distribution lines will be discussed. Results are presented for a variety of loads and load switching characteristics. The analytic tool employed is the TRW Engineering System Simulator (TESS) digital computer program, a modification of IBM's SCEPTRE circuit analysis program. TESS permits DC, AC, and transient analyses of systems containing non-linear as well as linear devices.

The basic configuration to be simulated is shown in Figure 3.2.2-1, and consists of a 120 VDC source, 50 meter transmission line, load power switch, and load impedance. The equivalent models for each of these elements are discussed below:

- (a) Source - The power source model, shown in Figure 3.2.2-2, is based on previous work (Reference 2) and simulates a 120 VDC fuel cell.
- (b) Distribution Cable - The 50 meter power cable was modeled using distributed transmission line parameters calculated for a (MSFC) #8 nickle coated wire pair, as determined in Reference 2. Figure 3.2.2-3 shows an equivalent circuit for a one meter segment of this line. In addition to the distributed capacitance, inductance, and resistance, the computed values of phase velocity (v) and characteristic impedance (Z_0) (assuming a nearly lossless line) are found to be 2.5×10^8 m/sec and 100 ohms respectively.
- (c) Power Control Switch - The switch characteristics were modeled after measured data for a solid state remote power controller (RPC) taken from Reference 3. The turn-off characteristics of the switch force load current to follow a linear ramp-off of 0.3 millisecond duration. The turn-on characteristic is an exponential function with a time constant of 35 μ sec. Leakage current in the

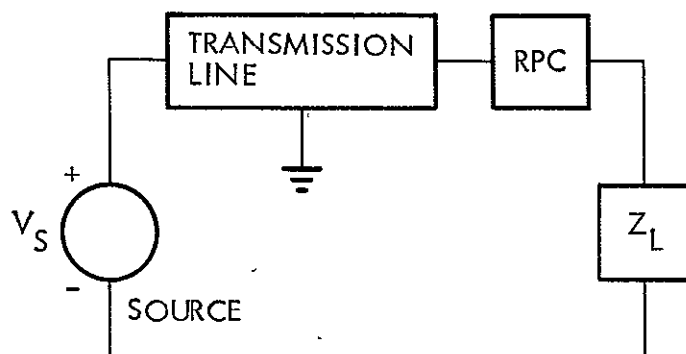


Figure 3.2.2-1. Components of Transient Analysis Model

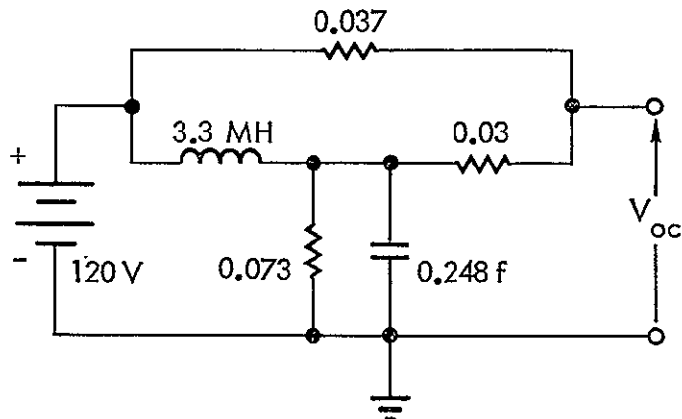


Figure 3.2.2-2. Source Model

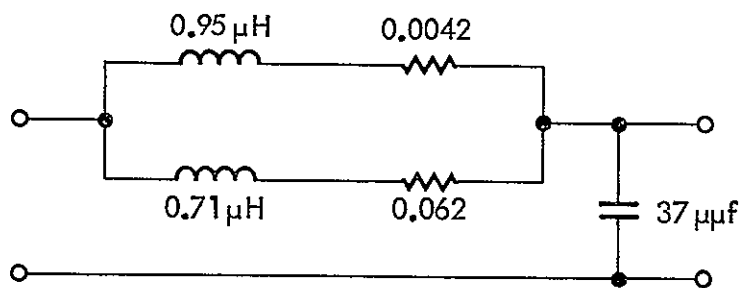
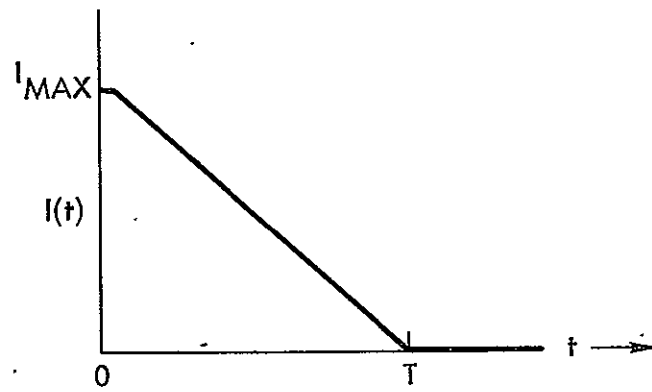


Figure 3.2.2-3. Equivalent Circuit for One Meter of Transmission Line

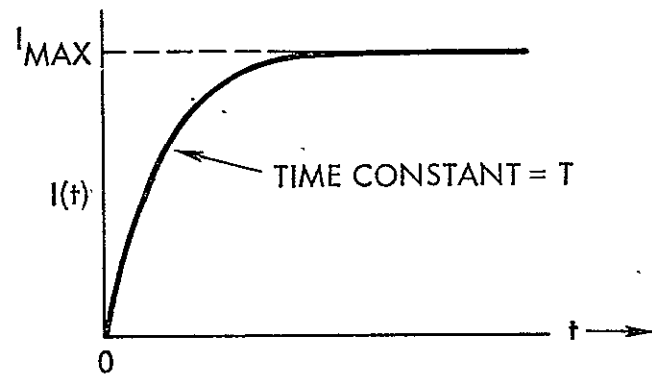
off mode was 1 microampere, and the resistance across the switch in the on mode was approximately 1/4 ohm. Since the performance of the switch is not the central issue in this study, a precise model was not attempted; rather, generalized switch resistance functions are desirable which permit the investigation of line transient behavior as a function of switching speed, load current, or other parameters of interest. The general forms of the turn-on and turn-off characteristics used are shown in Figure 3.2.2-4.

- (d) Loads - The loads analyzed included open and short circuits, ideal resistors, and a reactive load representative of a typical EMI power input filter. The latter is shown in Figure 3.2.2-5.

To verify the modeling approach, an initial test case was run for a 50 meter lossless line and nearly ideal load switch with a switching time of one nanosecond. Voltages and currents at the source, load, and at a point midway along the transmission line were computed as a function of time. With the switch initially closed, a steady-state load current of one ampere ($R_L = 120\Omega$) is assumed. The line is initially charged to 120 volts everywhere along its length. When the load switch is opened, the current into the switch is reflected back down the line toward the source, giving rise to a step increase in the line voltage at the load end of $\Delta V = I \cdot Z_0 = +100$ volts at $t = 0(+)$. The voltage step thus initiated is subsequently reflected alternately at the source and load ends of the line in accordance with the propagation time constant of the line ($T = L/v = 0.2 \mu\text{sec}$) and the source (short circuit) and load (open circuit) reflection coefficients of -1 and $+1$ respectively. The voltage at any point on the line can be determined from the simple diagram of Figure 3.2.2-6(a) by determining the net voltage from $t = 0$ to the time of interest. The resultant voltage functions at the load end (V_{50}) and at the halfway point on the line (V_{25}) are shown in Figure 3.2.2-6(b).



(a) TURN-OFF



(b) TURN-ON

Figure 3.2.2-4. RPC Switch Current Characteristics

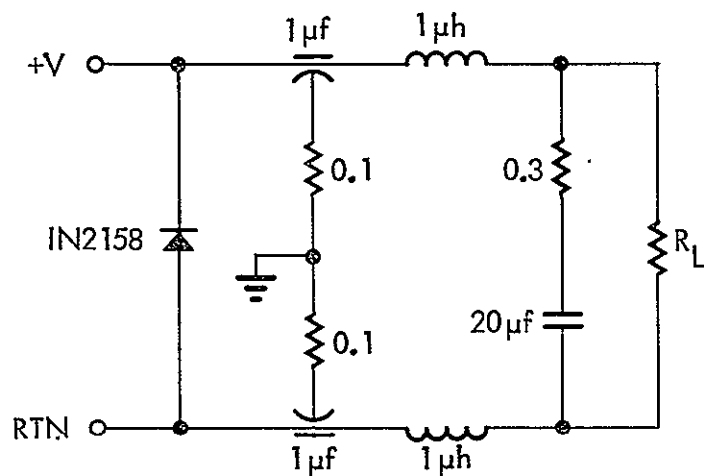


Figure 3.2.2-5. Load with EMI Filter and Suppression Diode

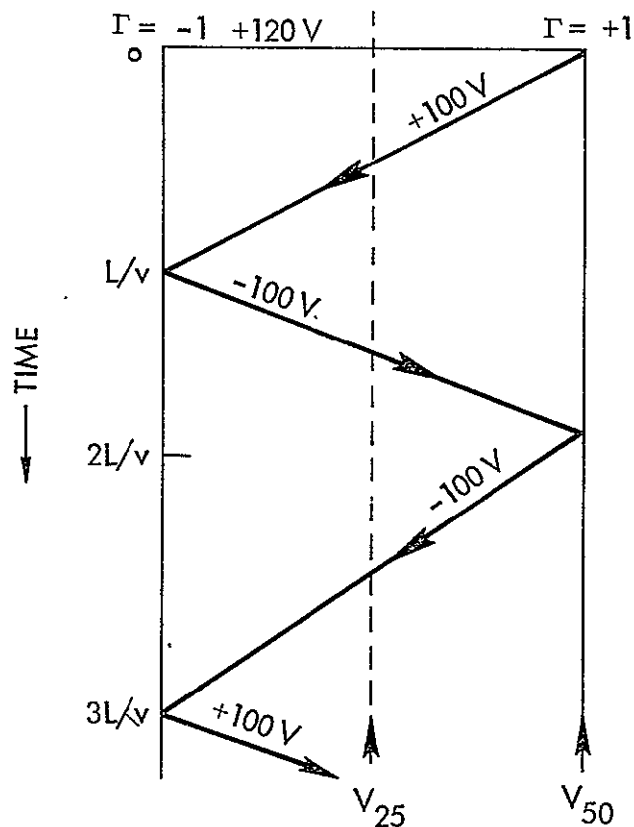


Figure 3.2.2-6(a). "Bounce Diagram for Determining Line Voltage as a Function of Time and Distance

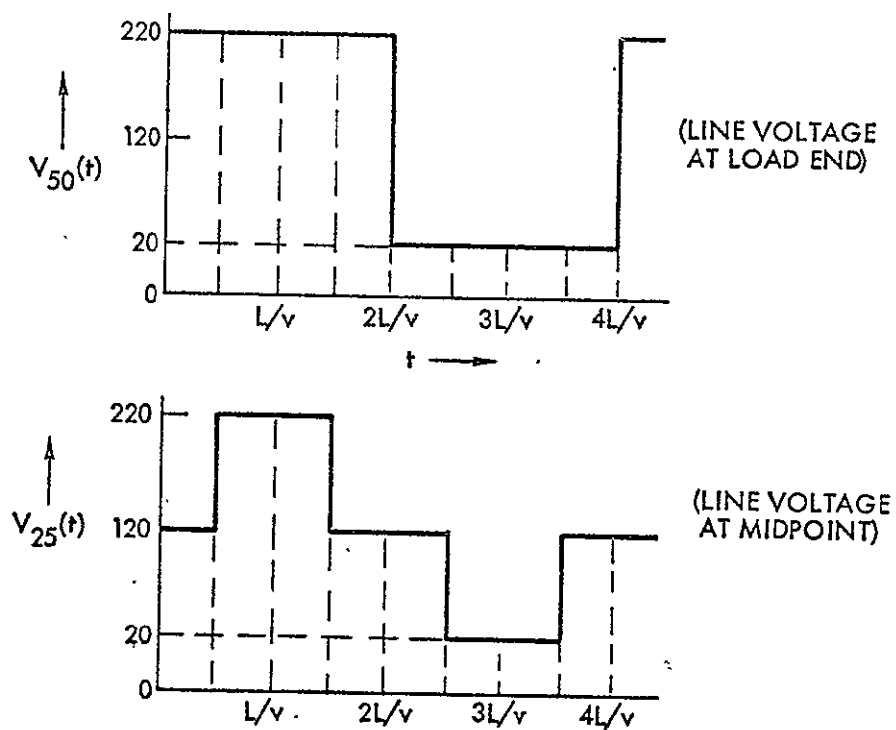


Figure 3.2.2-6(b)

The theoretical results predicted above for the lossless line are borne out by the computer program printouts shown in Figures 3.2.2-7 and 3.2.2-8. The rise time and oscillations at the leading edge of each voltage step are determined by the resonant frequency (approximately 40 MHz) of a single one meter section of the transmission line model.

The above run was next repeated with the 50 meter lossless line replaced by the distributed parameter model for the (MSFC) #8 wire. Over the simulation time of this problem, the results were not significantly different from those for the lossless line. Because of the large number of elements in the model (250 are required for the transmission line alone), and owing to the manner in which the program selects successive simulation time increments, the computation time was not sufficient* to observe the final steady-state conditions of line voltages and currents. The load-end voltage for this case, shown in Figure 3.2.2-9, clearly shows the round trip propagation time of the line (0.4 μ sec).

For non-ideal transmission lines considerable difficulty can be experienced in developing distributed parameter models which, with a relatively few elements, accurately simulate the transmission line characteristics for all frequencies. For this reason, a special run was made using one meter line segment equivalent circuits which yield the proper values of phase and attenuation constants in the vicinity of the transmission line quarter wave resonance frequency (1.25 MHz). The plot of line voltage at the load-end (Figure 3.2.2-10) shows the resultant damping of the line "ringing" initiated when the 1 ampere load is instantaneously switched off.

In all remaining runs, the transmission line model of Figure 3.2.2-3 was used. In the first of these, the 1 ampere load was switched off in accordance with the 0.3 msec ramp function corresponding to the RPC switching characteristic of Figure 3.2.2-4(a). In this instance a small

* A maximum computation time of five minutes was specified for all runs.

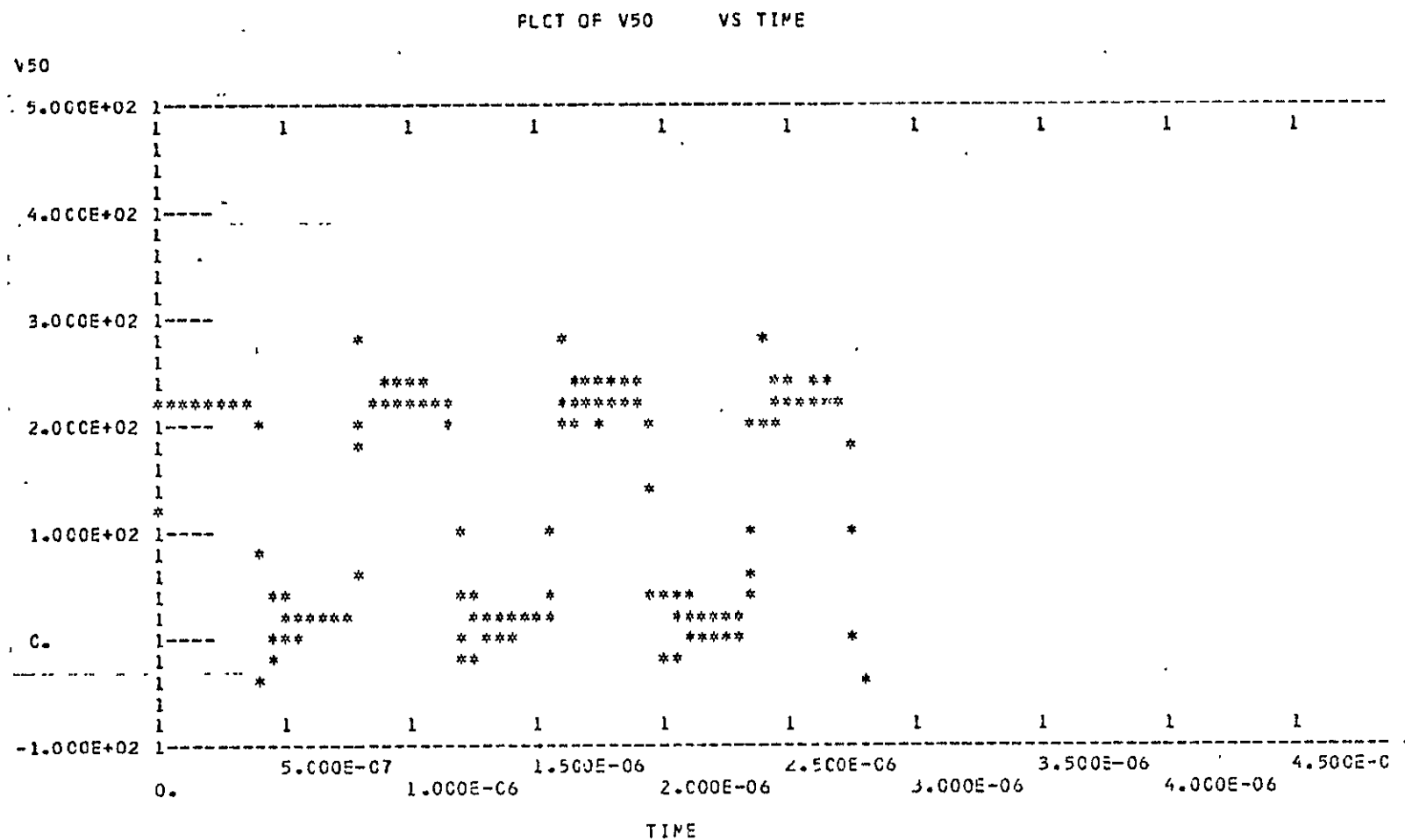


Figure 3.2.2-7. Lossless Line - Load-End Line Voltage

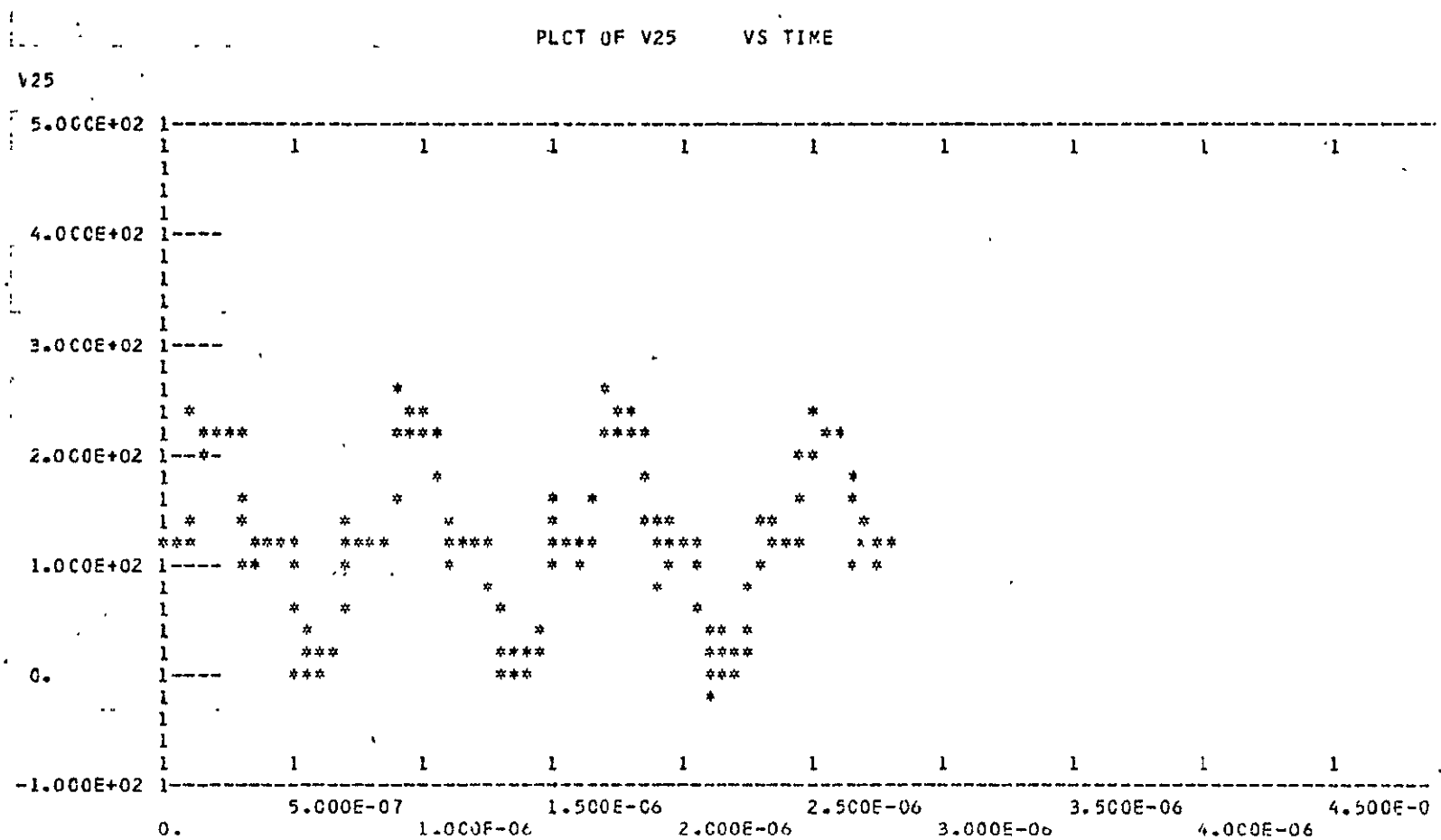


Figure 3.2.2-8. Lossless Line - Midpoint Line Voltage

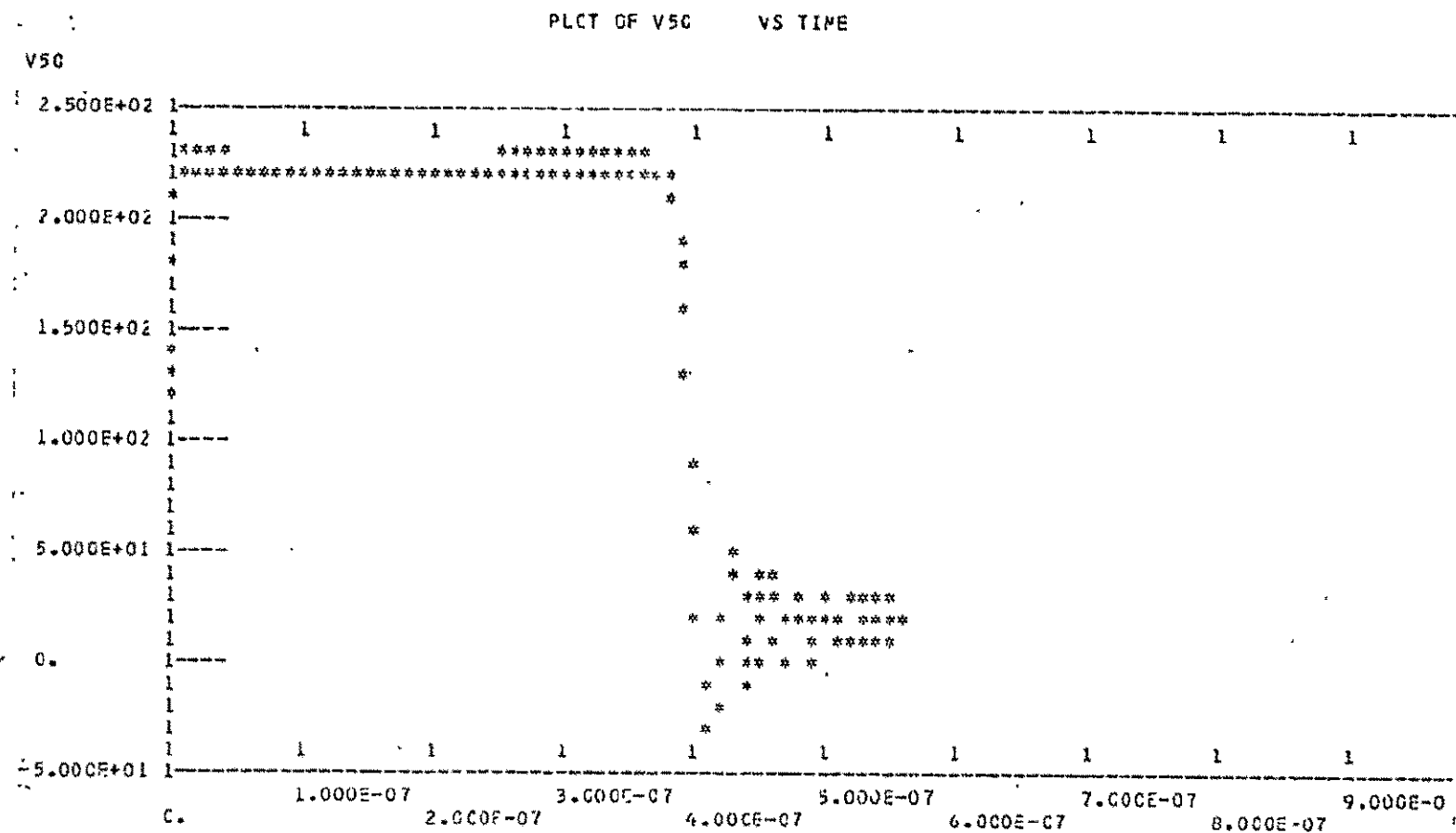


Figure 3.2.2-9. Lossy Line - Load-End Line Voltage

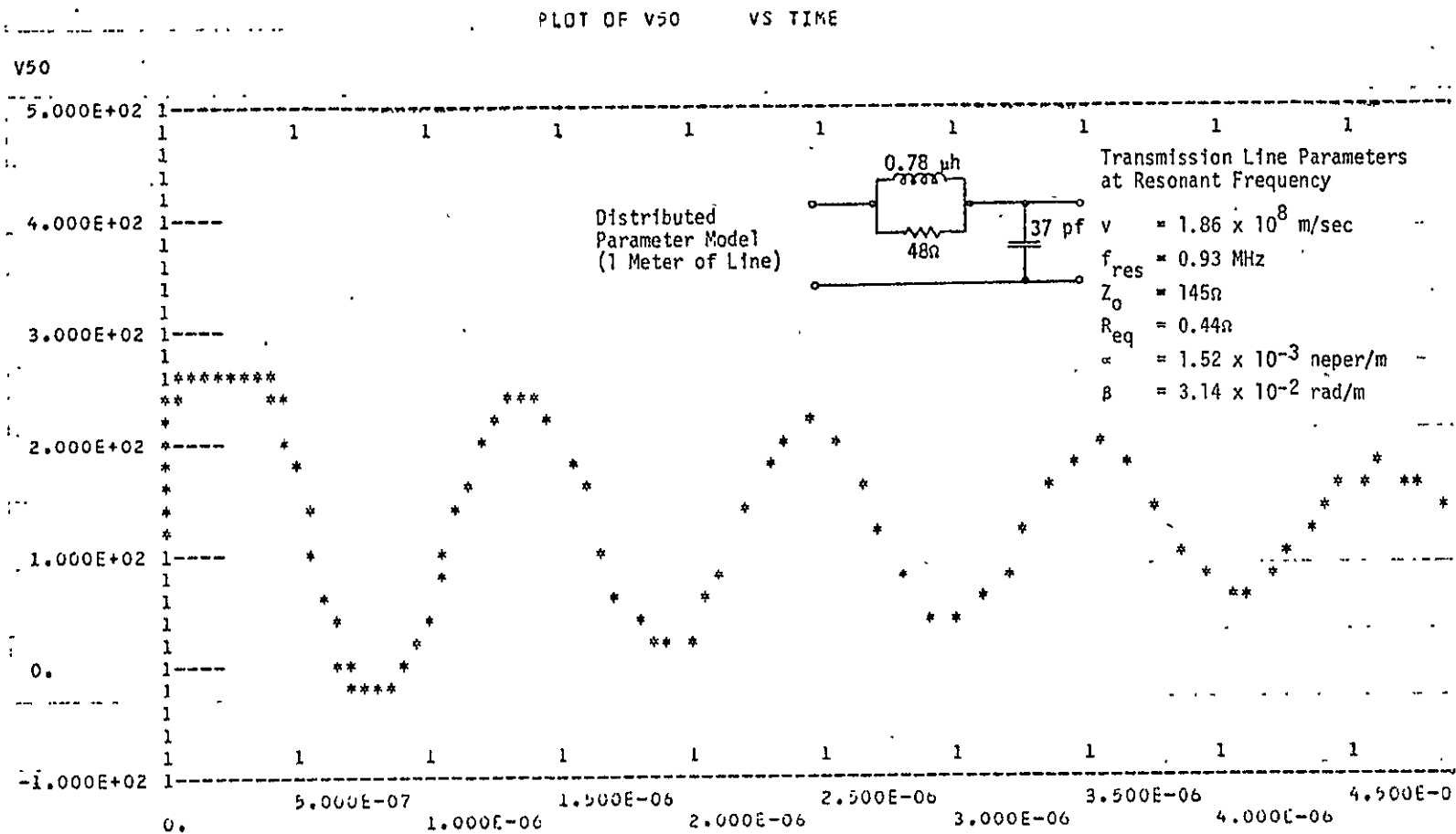


Figure 3.2.2-10. Load-End Voltage with Transmission Line Elements
Adjusted for Resonance (Switch-Off 120 ohm Load)

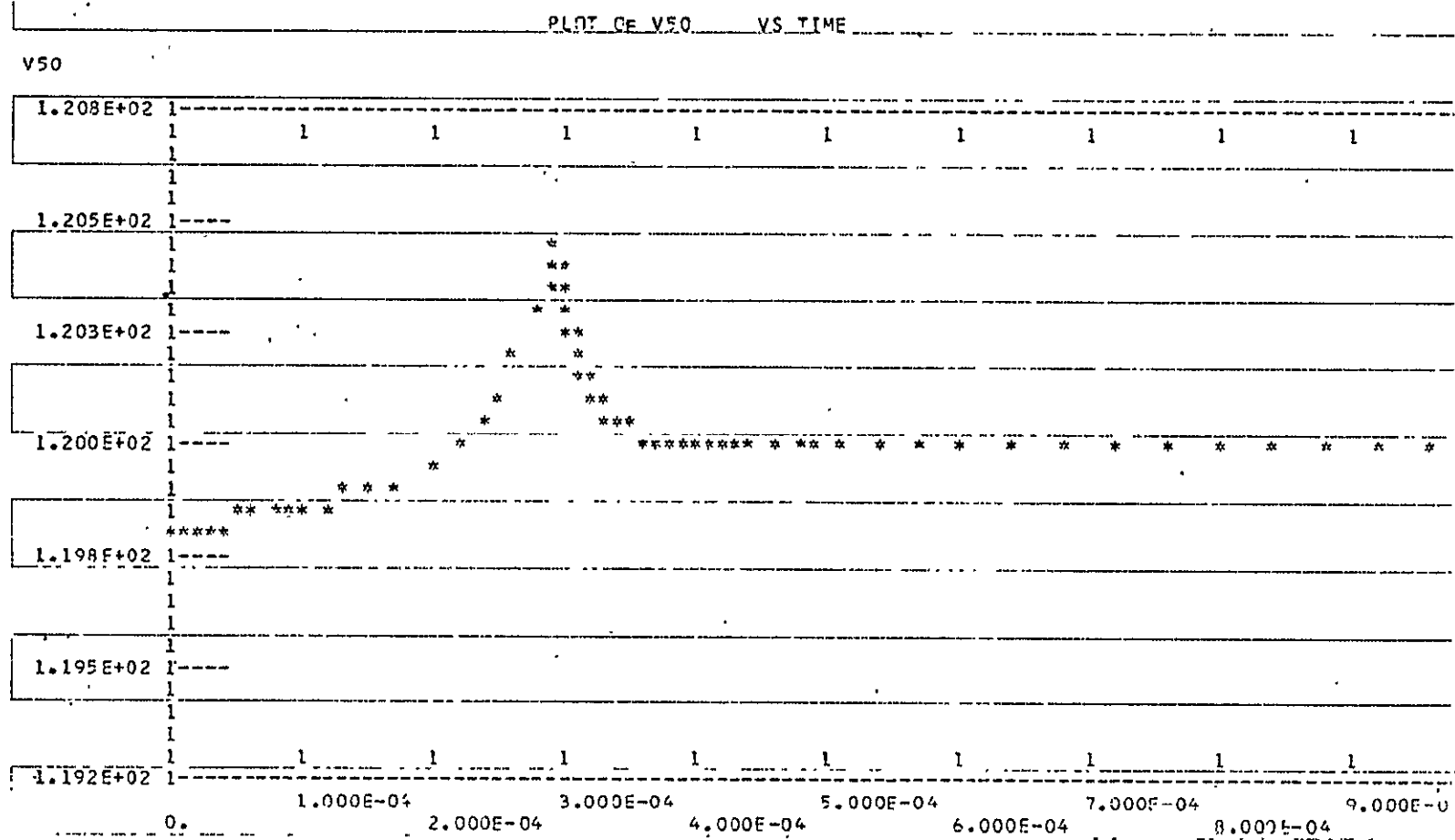
load-end line voltage transient of approximately 0.5 volts peak amplitude and 30 μ sec duration (Figure 3.2.2-11) occurs at the end of the switching time, decreasing in amplitude with distance toward the source. Of particular interest are the voltage across the switch, switch current, and switch power dissipation. These parameters, re-plotted from the printed data for ease of interpretation, are shown in Figure 3.2.2-12.

The above test was repeated with the RPC switching speed increased from 0.3 msec to 10 μ sec. The line voltage peak transient amplitude in this case was found to increase to 2.1 volts at the load-end as a result of the decreased switching time, still rather a benign effect. The voltage transient is shown in Figure 3.2.2-13.

As a final run using the 0.3 msec switch turn-off function, the line voltage was investigated for the load filter depicted in Figure 3.2.2-5. The resultant voltage transient (Figure 3.2.3-14), which occurs during the initial phase of the switching period, is of roughly the same amplitude and duration as that observed in the case of the resistive load.

The final two runs were performed for the RPC exponential switch-on function of Figure 3.2.2-4(b). The first of these utilized a 120 ohm resistive load and the second a resistive load plus EMI filter. The line voltage for the first case is shown in Figure 3.2.2-15. The exact cause of the oscillatory nature of the line voltage is still under investigation, but it is felt to be due to the abrupt discontinuity in the first derivative of the switch resistance at $t = 0$. Similar problems with the ramp-off function were observed in preliminary runs and were subsequently avoided by fitting a quadratic equation to the function and its first derivative at the break points. Since any physical process should be represented by a well behaved mathematical function, i.e., one which is continuous in all its derivatives, this aspect of the RPC switching models bears further examination.

Figures 3.2.2-16 and 3.2.2-17 show the results for the filtered load. The line voltage exhibits excursions of ± 14 volts about the nominal value of 120 volts at the load-end, decreasing to ± 8 volts at the 25 meter

Figure 3.2.2-11. 0.3 msec Switch-Off Transient - 120 Ω Load

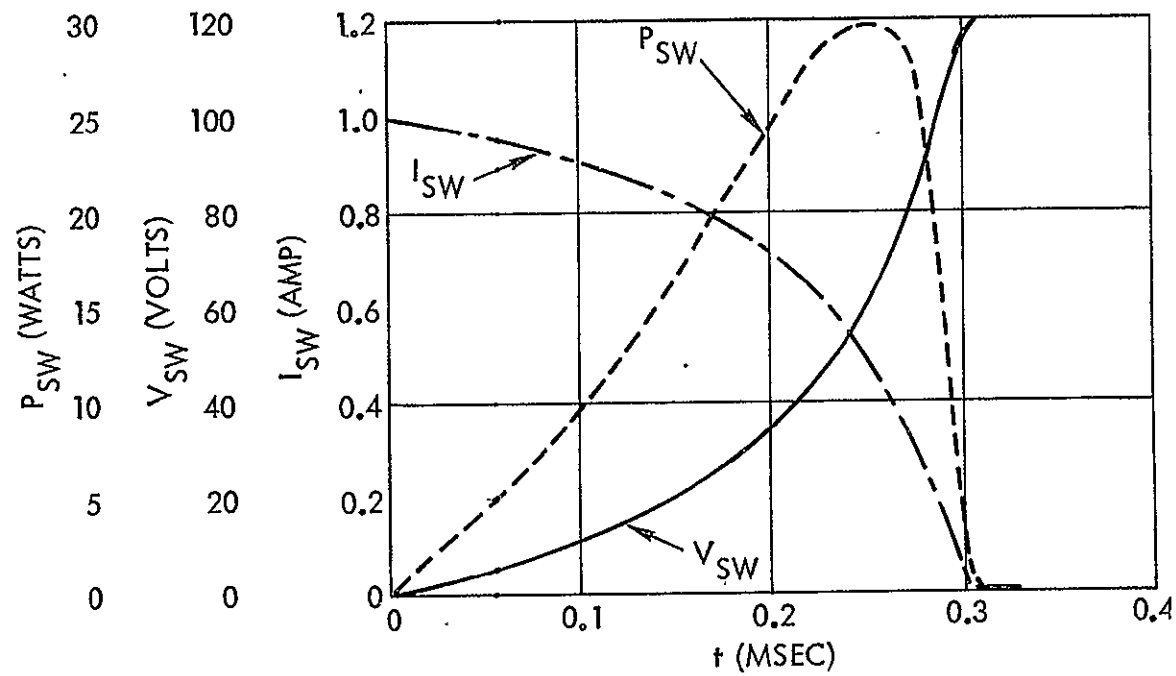


Figure 3.2.2-12 Switch Parameters for 0.3 msec Turn-Off, 1 amp Load

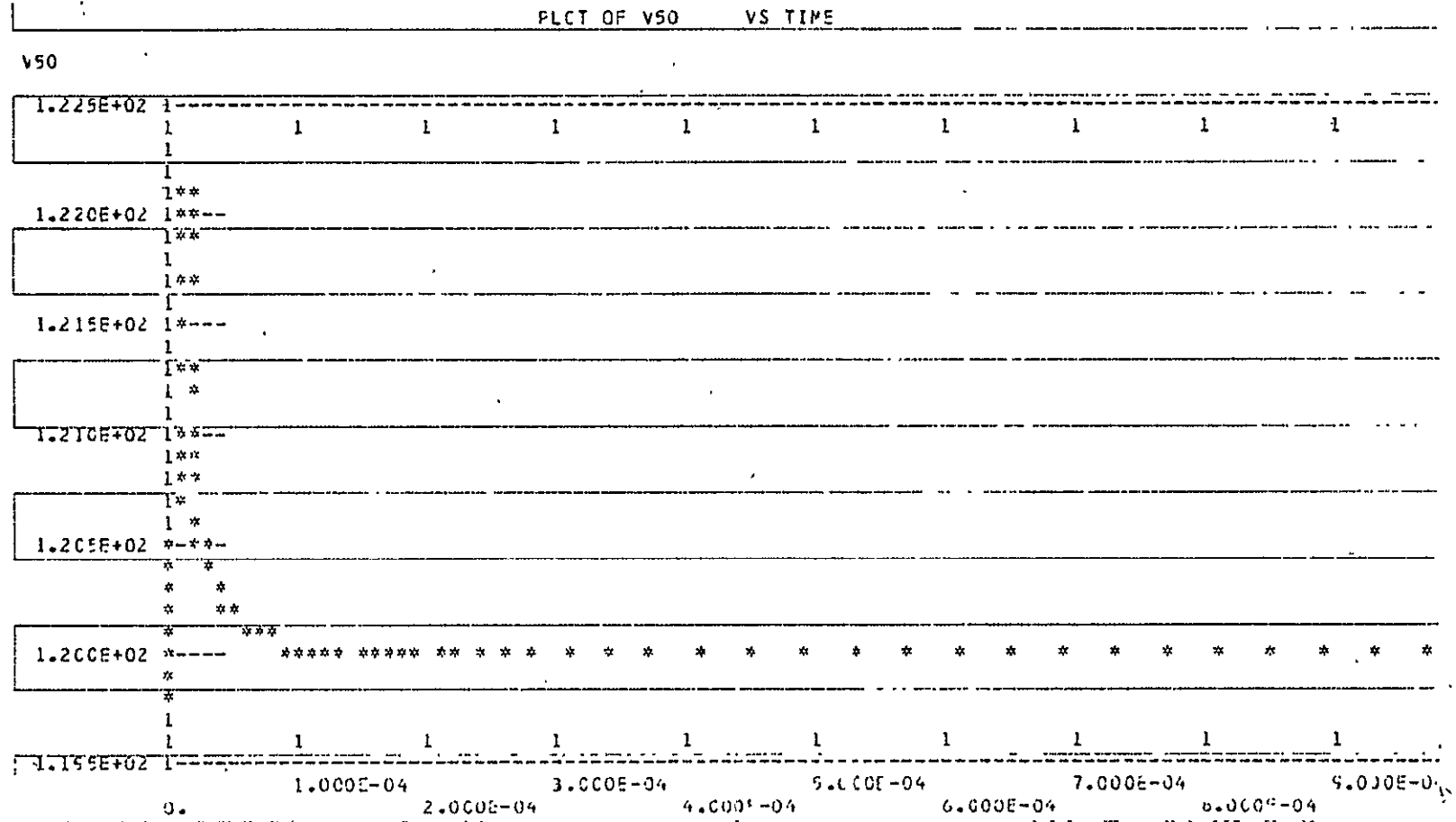


Figure 3.2.2-13. 10μsec Switch-Off Transient - 120Ω Load

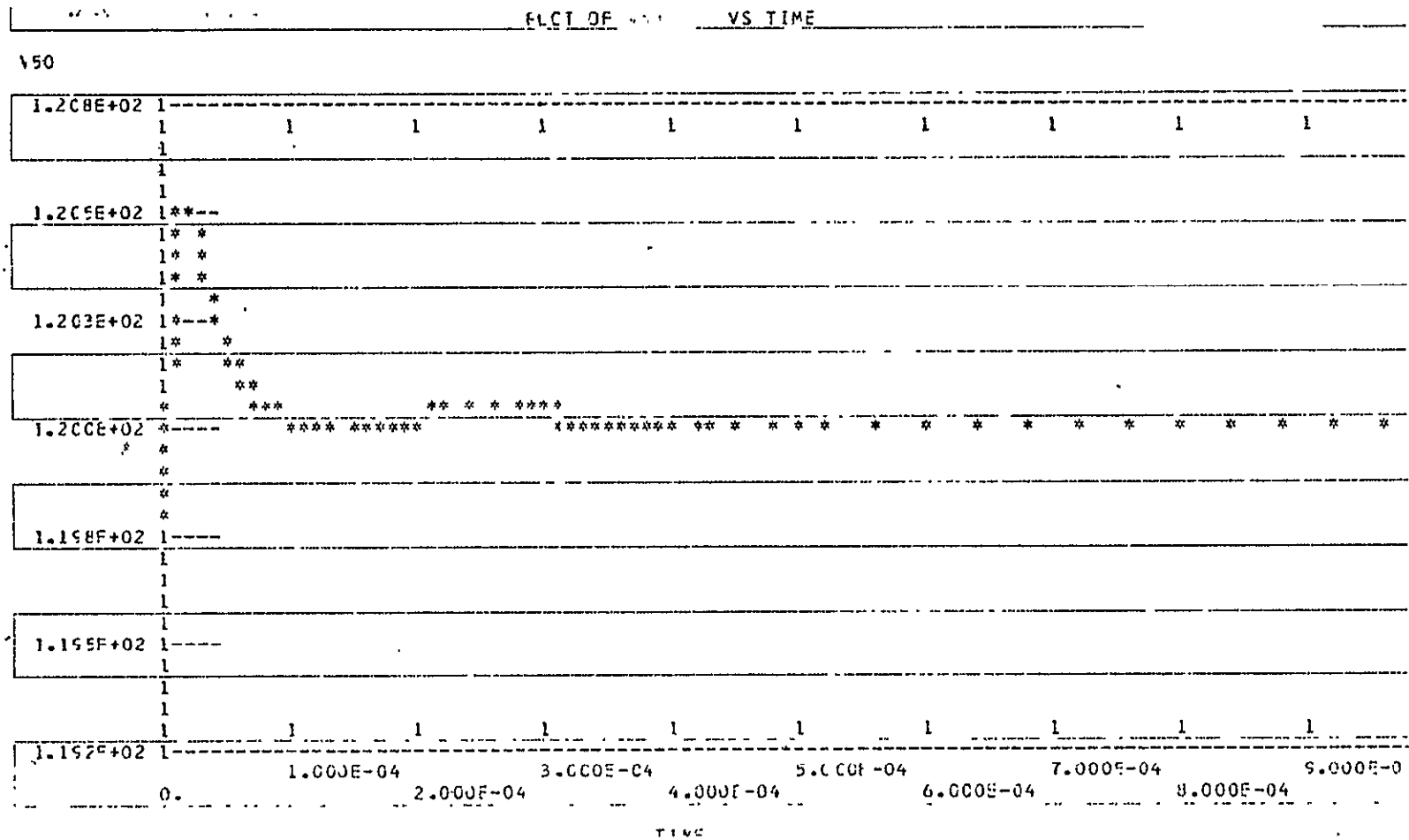


Figure 3.2.2-14. 0.3 msec Switch-Off Transient - Filter Load

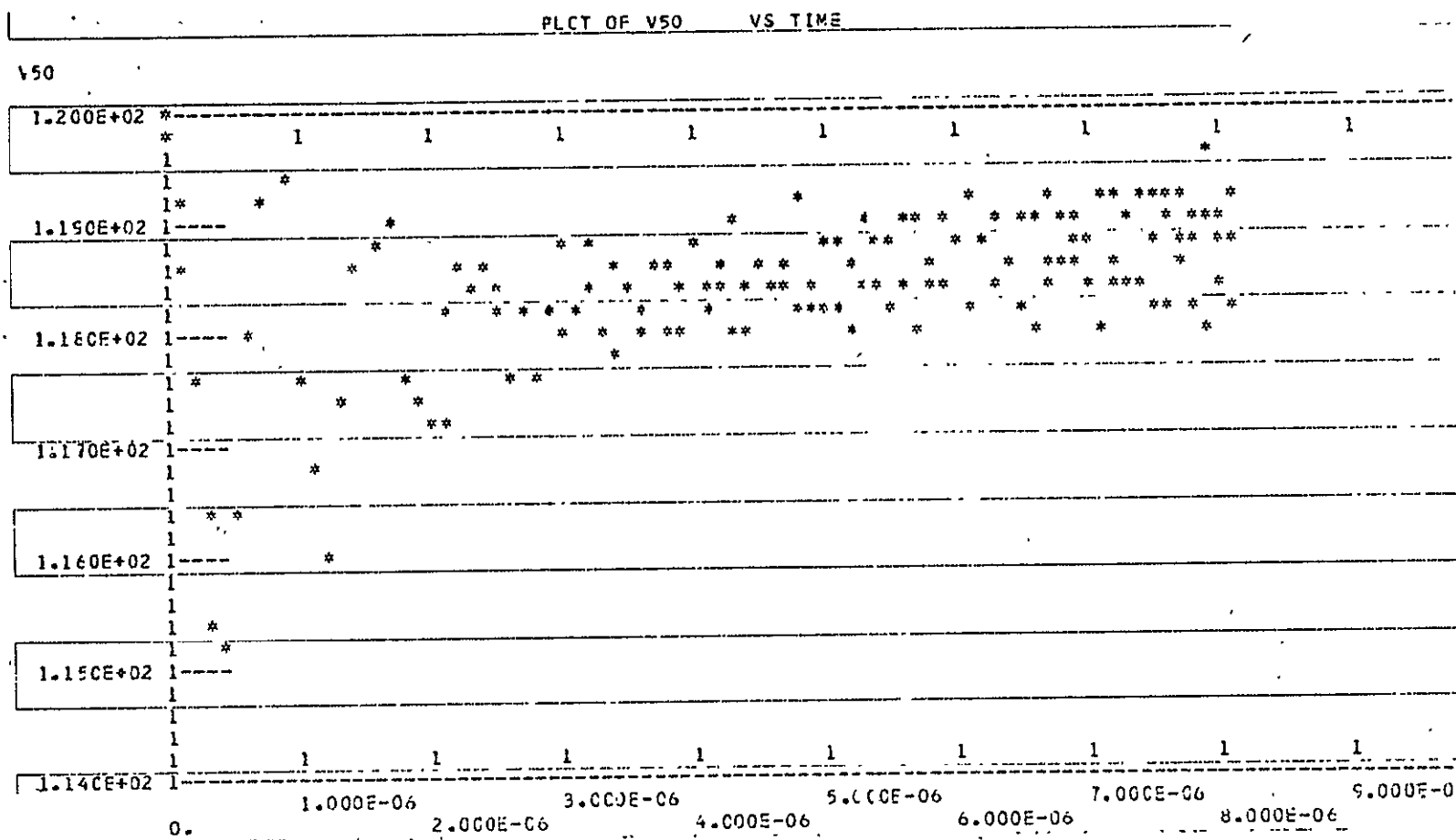


Figure 3.2.2-15. Exponential Switch-On Transient - 120 Ω Load

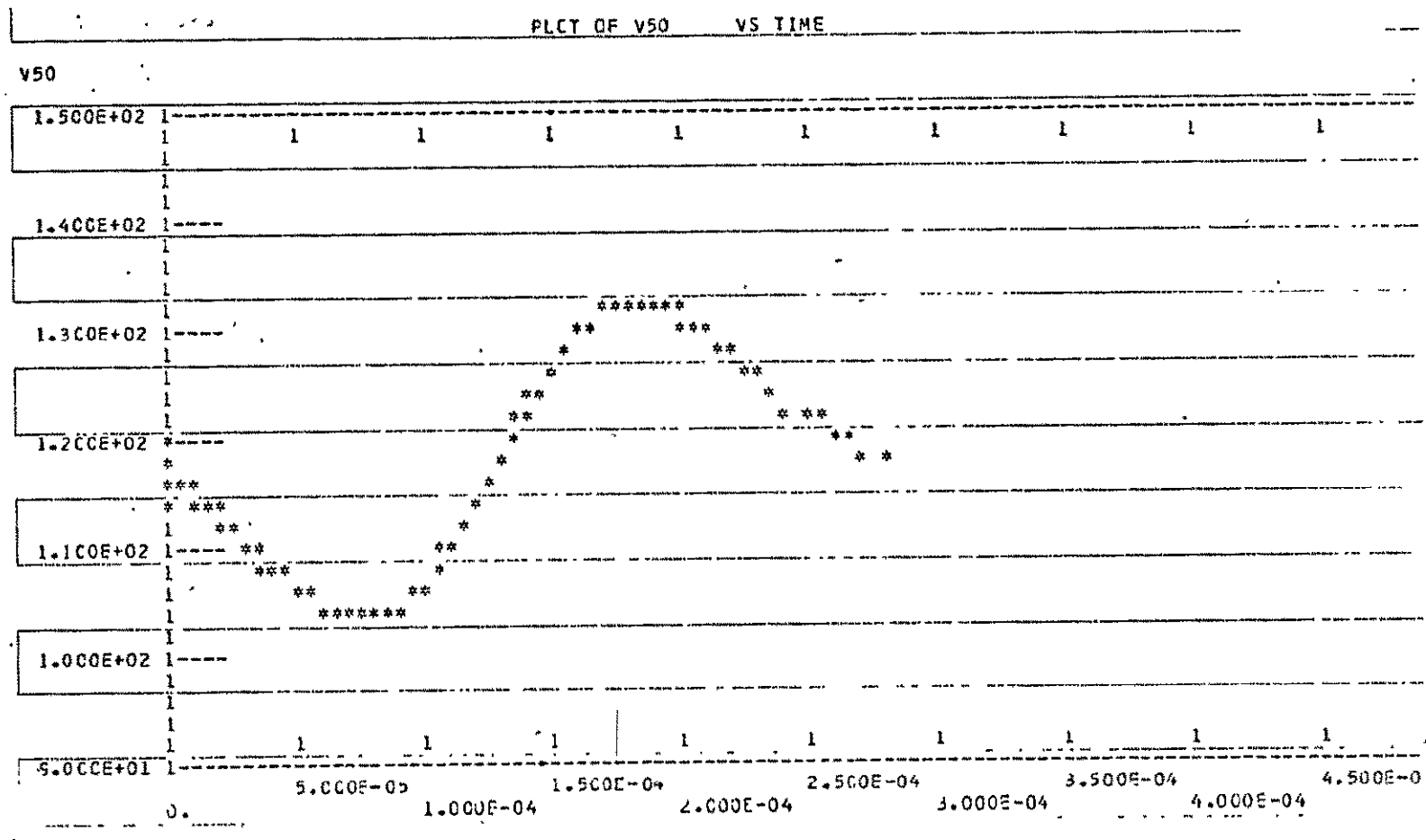


Figure 3.2.2-16. Exponential Switch-On Transient - Filter Load

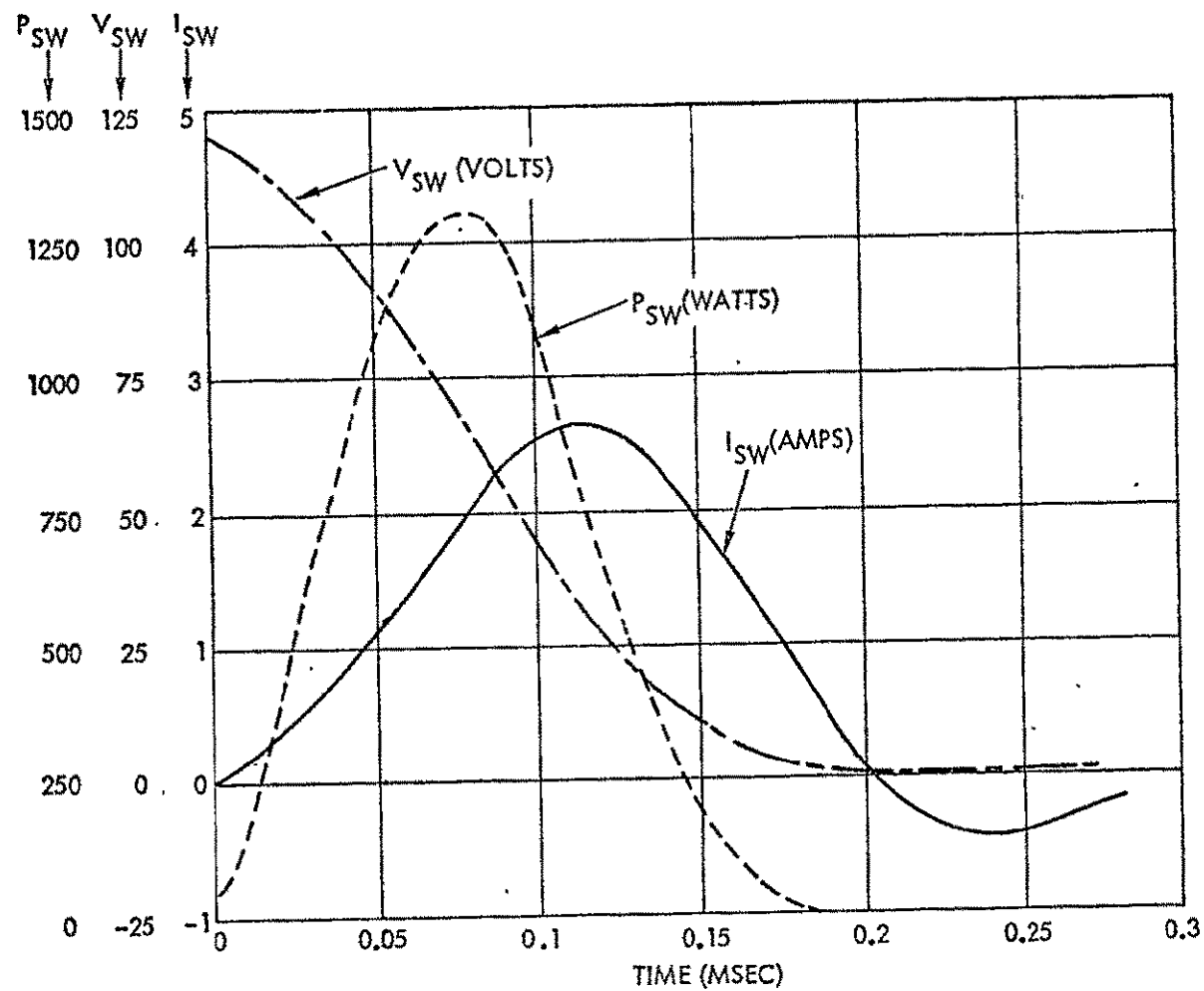


Figure 3.2.2-17. Switch Current, Voltage, and Power for Exponential Switch-On, Filtered Load

point. The high frequency oscillations observed for the resistive load above have been eliminated by the filter feedthrough capacitors with cutoff frequency of approximately 16 kHz. The peak inrush current (I_{sw} in Figure 3.2.2-17) for the filter element values chosen is 26 amperes, and the maximum instantaneous power dissipation in the switch is 1300 watts. The total energy dissipated by the RPC during the switching interval is approximately 0.12 watt-seconds.

3.2.3 Discussion and Conclusion

During the course of this study, contacts were established with power technology areas at Marshall Space Flight Center, Lewis Research Center, Naval Air Development Center (Warminster, Pennsylvania) and Wright Patterson Air Force Base (AFAPL) in an effort to obtain cable noise data on operating systems. This survey did not uncover a valid set of data which would characterize EMI on high power aerospace DC distribution cables. However, there are several technical centers which may yet yield significant information notably Johnson Space Center (Houston) and Naval Air Test Center, Patuxent River, Maryland. Further survey efforts will be determined by MSFC during future study efforts.

The data presented in Section 3.2 was extracted from reports on current designs at TRW and provide a relatively comprehensive evaluation of power subsystem noise characteristics for small spacecraft, but have limited value for predicting cable noise on large high power systems. This data does illustrate that although conducted narrow band noise currents correlate well with predicted values and the noise signals at the output of the power subsystem are well within specification, the relationship between noise voltages and currents at higher frequencies is not well defined. Furthermore, the beat effects which may be observed in the oscillograms indicate algebraic summing of signals. This illustrates the potential problems which may occur if r.m.s. summations are utilized in defining cable noise characteristics for large systems with many contributing components. Similar low frequency beat signals have been known to cause problems in the guidance actuator controls on Titan II and the attitude control electronics on OAO. Although these anomalies are normally detected during integrated system test, the diagnostic effort and modification required represent significant expense and schedule delay during critical system procurement phases.

Switching transient phenomena may be discussed in two categories:

- I. Transients due to charging and discharging filters at the load interface, actuator stall torques and initial currents of resistive heaters and lighting
- II. Transients due to abrupt changes in stored energy in distribution cables and due to switchgear operation (i.e., relay arcing, etc.).

The first group is related to lower frequency conducted and inductively coupled transients; the second group produces high frequency noise for which capacitive and radiative effects become significant factors. Filter design and distribution cable parameters provide a basis for comparison of power system performance at various levels of distribution voltage.

3.2.3.1 Filter Induced Transients

Filter induced transients occur during power switching events due to change of filter energy states. Transients at different voltage levels for equivalent designs may be compared on a variety of bases of which the most significant are peak current, pulse duration and total energy. If the only difference between subsystems is the distribution voltage, pulse duration and the spectral response of the filters will be similar and the peak value of the a turn-on current surge is easily characterized.

I_o = Nominal line current

I_p = Peak transient current

P_o = Nominal load power

E = Line voltage

For any fixed spectral response

$$I_p/I_o = K$$

$$\text{Since } I_o = P_o/E$$

$$I_p(E) = KP_o/E$$

Obviously this analysis favors higher distribution voltages since the peak transient current is inversely proportional to the line voltage.

However, there is a certain lack of realism in this analysis since filter design usually constrains transient peaks to a value which does not violate conducted interference requirements which are related to source impedance and system power capability. If it is considered that the design under comparison are optimized to meet N% regulation requirements and the source impedance from the load terminals is predominantly (long) cable resistance then the peak disturbance to the distribution line is,

$$\frac{E_p}{E_o} = \frac{I_p}{I_o} \frac{N}{100} = \frac{KN}{100}$$

which is independent of line voltage.

A more comprehensive evaluation of transient generation at various line voltages may be obtained by analysis of the change of energy states with comparable filter designs. Practical designs of power filters must be constrained by weight, size, damping factor and part limitations (primarily ac ratings of filter capacitors), as well as initial surge and spectral response. The automated filter design program developed in the first phase of this study addresses these constraints with the exception of the peak surge current which is a factor of approximately twenty-five to thirty for all designs,

$$K = I_p/I_o \quad 25 \leq K \leq 30$$

Since these designs are based on catalog part limitations and minimum weight, any reduction of initial surge specification would produce an increase in weight for all designs. Performance analysis of these filters results in an estimate of the minimum energy of the filter induced transients at all voltage levels. Minor modifications to the filter design program provides this data which is presented in Figure 3.2.3-1(a) and (b). All filter designs were assumed to be interface circuitry for a pulse width modulator operating at 50% duty cycle and a spectral attenuation characteristic which meets MIL-STD-461A as developed in Reference 2. Figure 3.2.3-1(a) provides a comparison of 28V and 120V operation for a 1.0 KW PWM over the potential range of operational frequencies. It is noted that the stored energy for 120V is approximately twice that for 28 volts. This reflects the fact that the energy stored in these power filters is primarily capacitive.

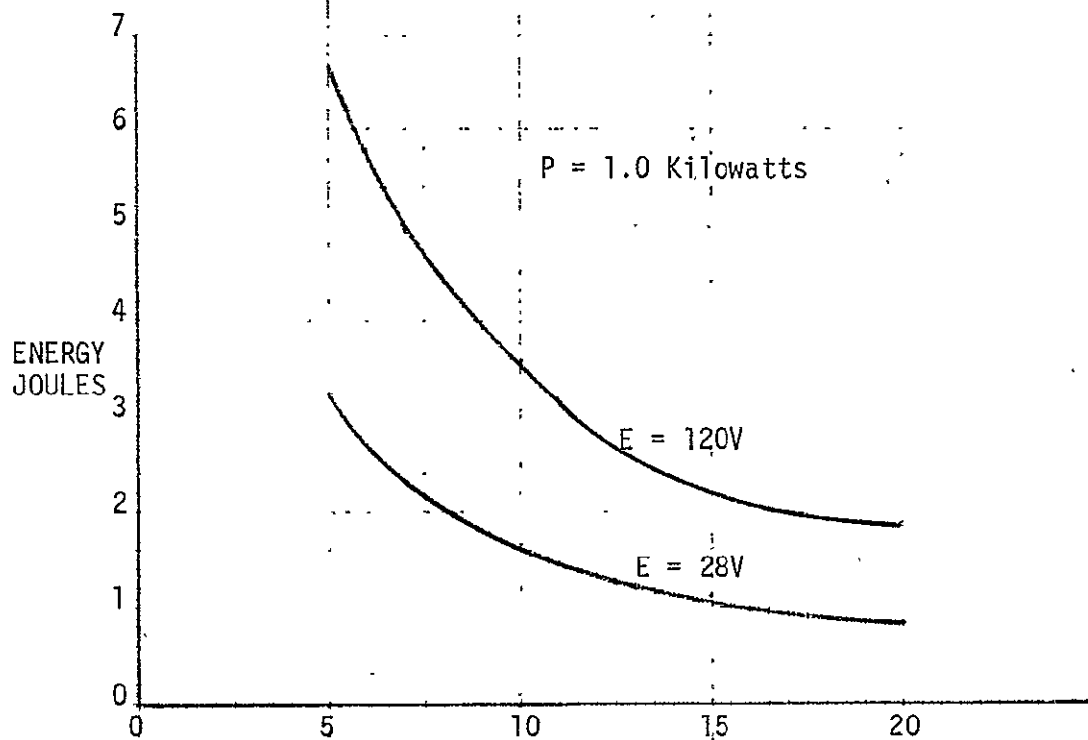


Figure 3.2.3-1(a). PWM Frequency ~ Kilohertz

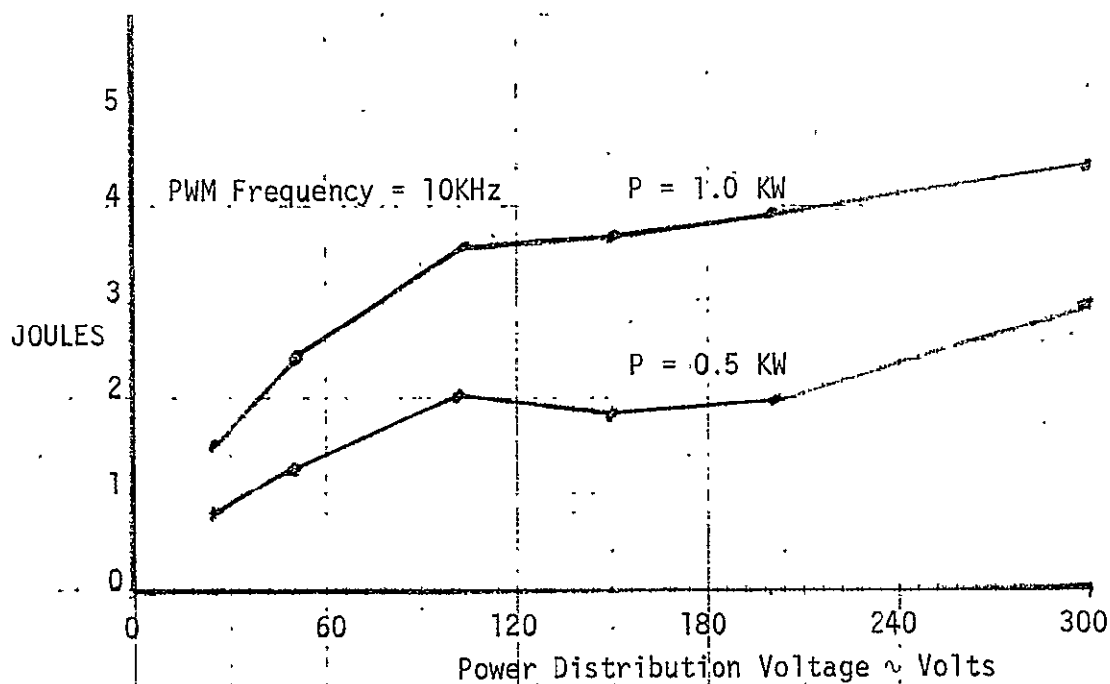


Figure 3.2.3-1(b). Stored Energy ~ Pulse Width Modulator Filter

Reduction in the initial surge would increase the inductance of the filters and tend to move the curves closer together. Figure 3.2.3-1(b) provides a similar comparison for a continuous range of line voltages for two power levels. The lack of linearity is due to the design program selecting capacitors with currently available characteristics. For a particular system design where the bases for transient constraints are established (i.e., peak current, regulation requirements, etc.) an estimate of the filter transient effects may be obtained from this form of parametric study.

3.2.3.2 Cable Induced Transients

The simulations of Section 3.2.2 of this report were performed to evaluate the nature and amplitude of electrical stress on switchgear with long cables. Difficulties were encountered due to the large number of elements required and the non-linear (frequency) characteristics of the distribution cable parameters.

The transient which occurs on a long cable is defined by the characteristic (surge) impedance and the rate of change of terminal induced currents. Simulation of the cable by a simple lumped constant network would not display the effects of multiple reflection. Any distributed model which does not utilize many elements in each network approximates an ideal transmission line for the major portion of the frequency and obscures significant attenuation constraints. If a simulation is intended to be valid to 10 MHz each network section should not represent a cable length not in excess of two meters. An effective frequency model would require each network to contain a series RL circuit for each octave of frequency above 1 KC and one capacitor. For a 50 meter cable the number of parts is approximately,

$$n = \frac{50}{2} [1 + 2 (\log (10^7/10^3))/\log 2], \approx 725$$

The cost of performing simulations with this number of parts at the high frequencies involved (≈ 2 MHz) becomes excessive. Consequently the majority of the runs were performed with a model which provided an accurate simulation at frequencies below 20 KHz and approximated a lossless line at frequencies in the MHz range. Due to these factors, the fast switching transients resulted in multiple reflections with little attenuation. However, the magnitude of the signals is considered accurate and attenuation may be extrapolated from the calculated cable constants. Significant factors with respect to solid state switch interfaces were defined as follows,

- (1) Maximum voltage across the switch for essentially zero switching time is,

$$E_p = I Z_o$$

I = Line current prior to switch (off) operation

Z_o = Cable characteristic impedance.

- (2) Voltage across switch during (off) transients may reverse due to capacitive loads and reflection of wave fronts at cable terminations
- (3) Current through the switch during (on) transients may reverse with LC input filters.

The high voltage transient (Item (1)) will contain energy which is a function of line current, voltage and cable parameters. For the nickel plated conductor and the 50 meter length under consideration the magnitude of this energy is given below,

$$W (120V, 1.0 \text{ KW}) = 1.15 \text{ Millijoules}$$

$$W (28V, 1.0 \text{ KW}) = 21.0 \text{ Millijoules}$$

$$L = 50 \text{ meters, nickel plated \#8 conductor pair}$$

In these calculations it is apparent that the inductance of the cable predominates. The potential amplitude of this transient is of the order of several thousand volts or higher when the switch is acting as a breaker under line fault conditions. Solid-state switchgear will limit transients to the breakdown voltage of the semiconductor switch if this is an acceptable approach, otherwise the subsystem design should include a small RC circuit across the line immediately preceding the switch. The normal slow switching rates of solid state switchgear ($t > 10 \mu s$) will result in negligible transients for 50 meter lines.

REFERENCES

1. Final Report, "Space Vehicle Electrical Power Processing, Distribution, and Control Study," A. Krausz.
2. "Research Study on Multi-KW DC Distribution System," E. A. Berkery and A. Krausz, May 1975.
3. "Aerospace Technology Development of Three Types of Solid-State Remote Power Controllers for 120 VDC," Westinghouse Electric Corp., February 1975.

3.3 BUS CONTROL UNIT (BCU)

3.3.1 Introduction

The BCU consists of a standard equipment rack containing switchgear for load fault isolation and power source control. Electronics are included to provide remote and local supervision functions.

The BCU provides the electrical interface between the power sources and the power distribution cable and simulates the electrical characteristics of a space vehicle power distribution control panel. The functions performed at a flight design panel normally consist of power control of major subsystems, power distribution fault removal, and redundancy switching. Instrumentation is minimal and consists of bilevel signals to indicate the state of contactors or circuit breakers and one voltage and current measurement per source; displays are located remotely in the pilot's cockpit. There are usually two redundant power distribution systems which have interconnection capability so that failure of a power source or a distribution cable will not cause electrical system failure. Each distribution system has the capability of performing its function at the full power level required by the load utilization equipment. Mission planning does not normally include the reactivation or attempted reuse of a failed portion of the system. The switching requirements for any one flight system are consequently limited in complexity with only a few switching cycles performed by the main bus contractors.

The major elements of the BCU are illustrated in Figure 3.3.1-1. The BCU will be able to simulate redundant configurations and provide local control and monitor functions; remote functions are provided by the SMU (Supervision and Monitor Unit) and ACES (Automatically Controlled Electrical System) in combination with the BCU on a logical "OR" basis. Provision is made for remote monitoring of outputs from all BCU instrumentation circuitry. The electronics provides signal conditioning and control functions and logic designed to prevent inadvertent paralleling of power sources. Override control is provided for tests in which paralleling of power sources is desired and warning signals indicate if this condition is present. Due to the necessarily variable level of the DC line voltage, all power converters, electronic circuits and relays operate from an ac powered 28 Vdc supply. The 28V is distributed to the load banks where further conversion is provided as needed for control electronics.

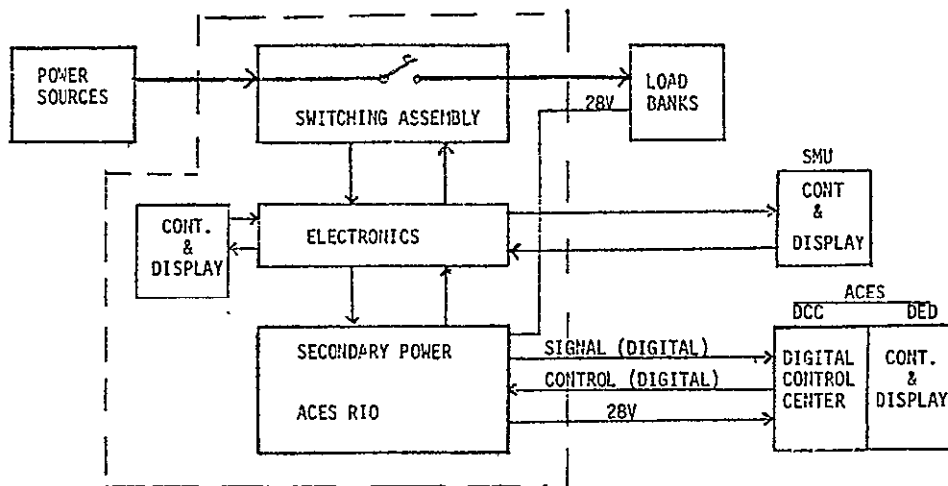


Figure 3.3.1-1. BCU Interfaces

3.3.2 Switching Assembly

The switching assembly (Figure 3.3.2-1) provides all switching and breaker functions for the power sources, main and load fuses. Current flows from the batteries and power supplies through contactors (K1-K8), main bus breakers and load bus terminals. Connectors for power sources and load buses will consist of terminal lugs for minimum contact resistance. Conductors in the main power bus paths should be rated at 300A and 300 volts steady state. Current peaks of 1000A may occur for periods less than 100ms during load faults.

Voltage status is sensed for each power source, main bus and load bus by circuitry which responds to voltages in excess of 20V. These signals are displayed on all monitor equipment simultaneously to enable quick assessment of the state of contactors and breakers. Voltage measurements are obtained from the input side of the power source contactors. This configuration provides adequate data on voltage in the system and facilitates paralleling sources and battery charging. Battery charging by the power supplies is

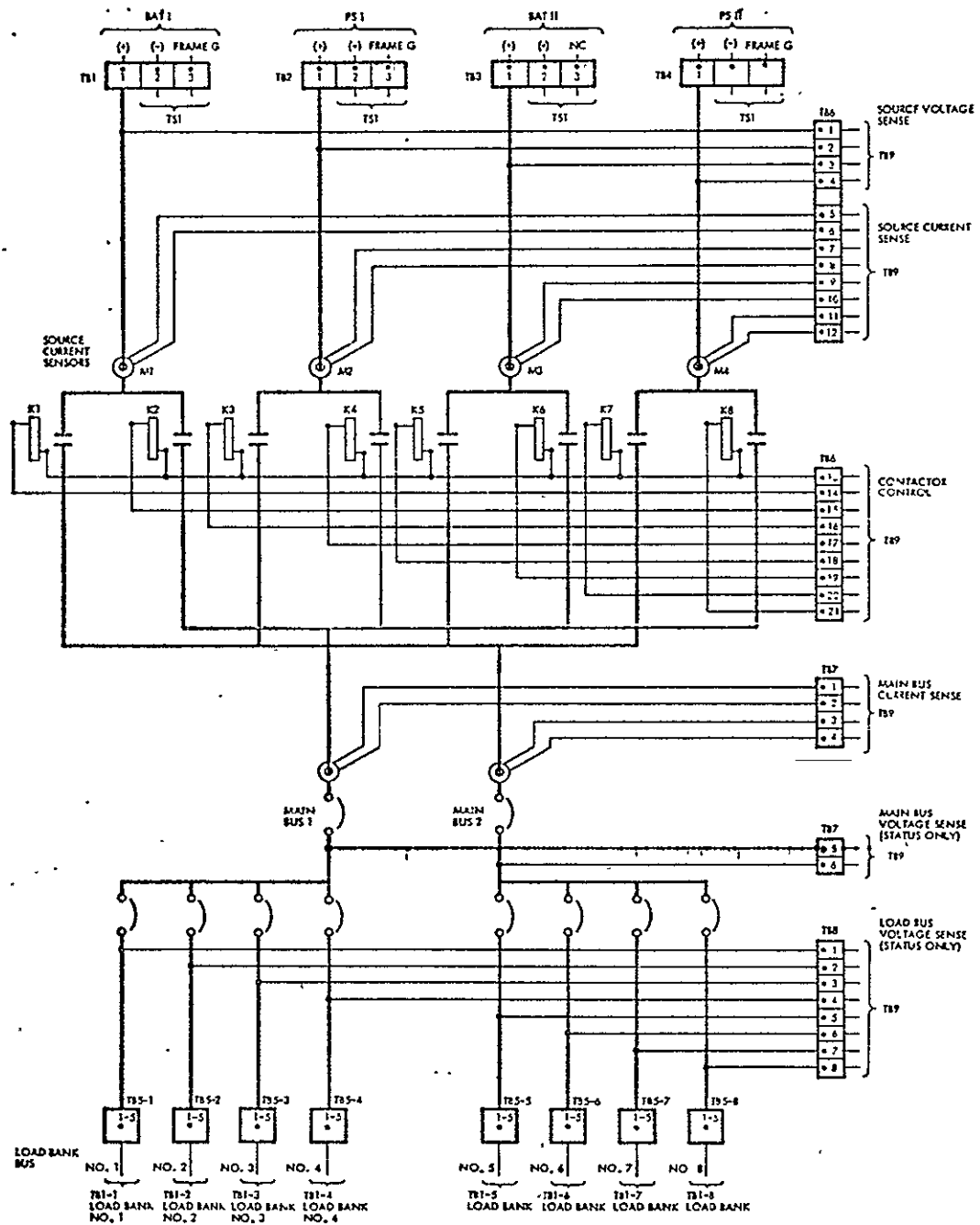


Figure 3.3.2-1. BCU Main Power Switching Assembly

implemented through the BCU and is described in Section 3.4.4 of the May 1975 report on this contract. Magnetic current transducers monitor power source and main bus current; load bus current is measured at the load banks. The use of these current transducers is preferred over current shunts because of the improved isolation obtained between instrumentation and the HVDC line (28V-300V). These devices are also relatively impervious to excessive fault currents and do not increase the number of contacts in the power bus circuits.

The use of AC powered devices in the BCU is acceptable and reduces the procurement cost of these instruments. Some modifications of the instrument design may be necessary to obtain the dual outputs for the BCU and SMU panel. An alternate approach using current shunts in the power return is viable but will not register structural fault currents and introduces contact resistance in the power circuits.

The eight power contactors (K1-K8) connect any selected power source to either main bus. This design provides flexible reconfiguration capability without manual adjustments on equipment carrying hazardous voltages. Since the inadvertent connection of two power sources to the same bus could result in large circulating currents, an inhibit function is included in the logic. The inhibit function may be removed by a command from any of the control panels when operation of parallel sources is desired.

3.3.3 Secondary Power Distribution

Secondary power (28VDC) is distributed to the BCU electronics, SMU, load banks and ACES subsystems as shown in Figure 3.3.3-1. Power conversion from 28VDC to other voltage levels is provided in each subsystem as required. Since AC operated equipment is permitted in the BCU, AC/DC power supplies are used in this component. Single phase 115V AC 60Hz is tentatively shown as being distributed to the BCU electronics to operate the six magnetic current transducers. Further evaluation of the current transducers may indicate a need for an isolation transformer and/or reduced voltage levels. The central ground point is located in the BCU and provides a ground termination for all equipment and the laboratory (building) ground.

The ACES RIO (Remote Input/Output Unit) provides commands to the BCU and monitors bi-level status signals. All ACES controls and signals are duplicated on the BCU and SMU panels. The harness from the RIO to the ACES

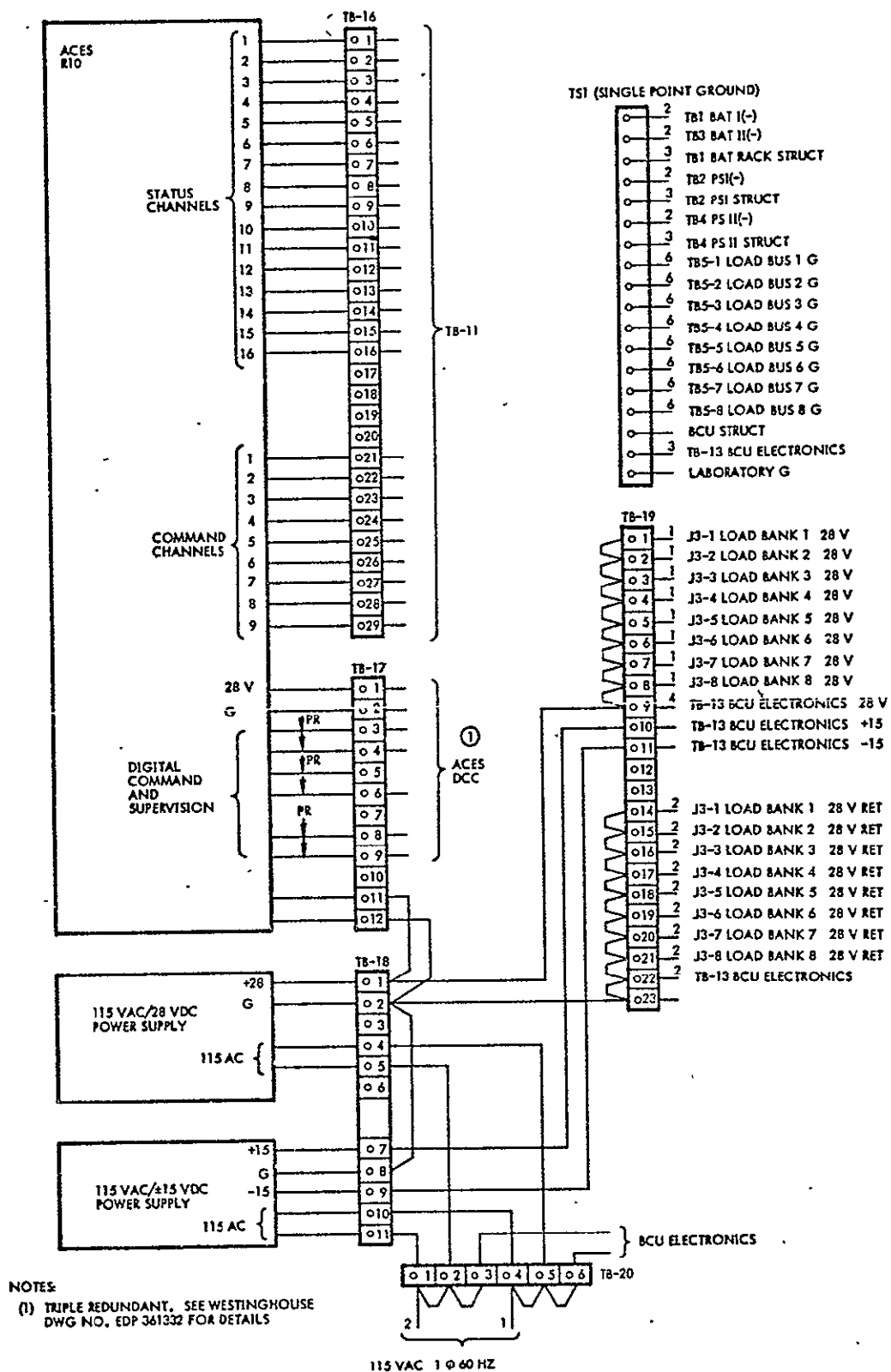


Figure 3.3.3-1. BCU Power Distribution and ACES R10

DCC (Distribution Control Center) includes the 28V DC bus which supplies power to the DCC and the DED (Data Entry and Display Panel).

3.3.4 Control and Display

The BCU control panel (Figure 3.3.4-1) includes functions normally located on a power distribution panel for a flight vehicle as well as functions necessary to provide unique reconfiguration and test control capability required for the HVDC test program.

The basic control and monitor functions for a flight vehicle power distribution panel consists of capability to energize the main buses, protection against major line faults and a minimal status display; operation of line contactors may be provided by local or remote control. The BCU power source contactors are operated from the BCU, SMU and the ACES DED on a logical "OR" basis. Panel indicators respond to presence of voltage at each source power input, and the output side of the main bus and load bus breakers. Panel lights are arranged to roughly simulate the switchgear configuration to enable the operator to obtain "quick look" status of the power distribution system. Panel meters provide measurements of voltage and current for each source and main bus current. In addition to providing performance data on each source, panel voltmeters are necessary to match voltage levels prior to paralleling power sources or battery charging operations. Parallel operation of a power supply and a battery is required to supply high peak loads or during the simulation of major line fault transients. The switching configuration for battery charging requires the closing of a battery contactor and a power supply contactor to a main bus with the main bus breaker operated to the "OFF" position. Normal test operations may be continued with the power sources and main bus not involved in the battery charging function.

The inadvertent connection of more than one power source to a main bus could result in large circulating currents with potential damage to contactors and power source harness. In order to reduce this possibility, warning and inhibit functions have been included in the BCU design. With the "Parallel Source Enable" switch in the "OFF" position, the inhibit function will prevent the connection of two power sources to the same main bus. Attempts to establish such a connection will result in operation of the "Parallel Alert" indicator. Operating the "Parallel Source Enable" to the "ON" position removes the inhibit function but will continue to provide a

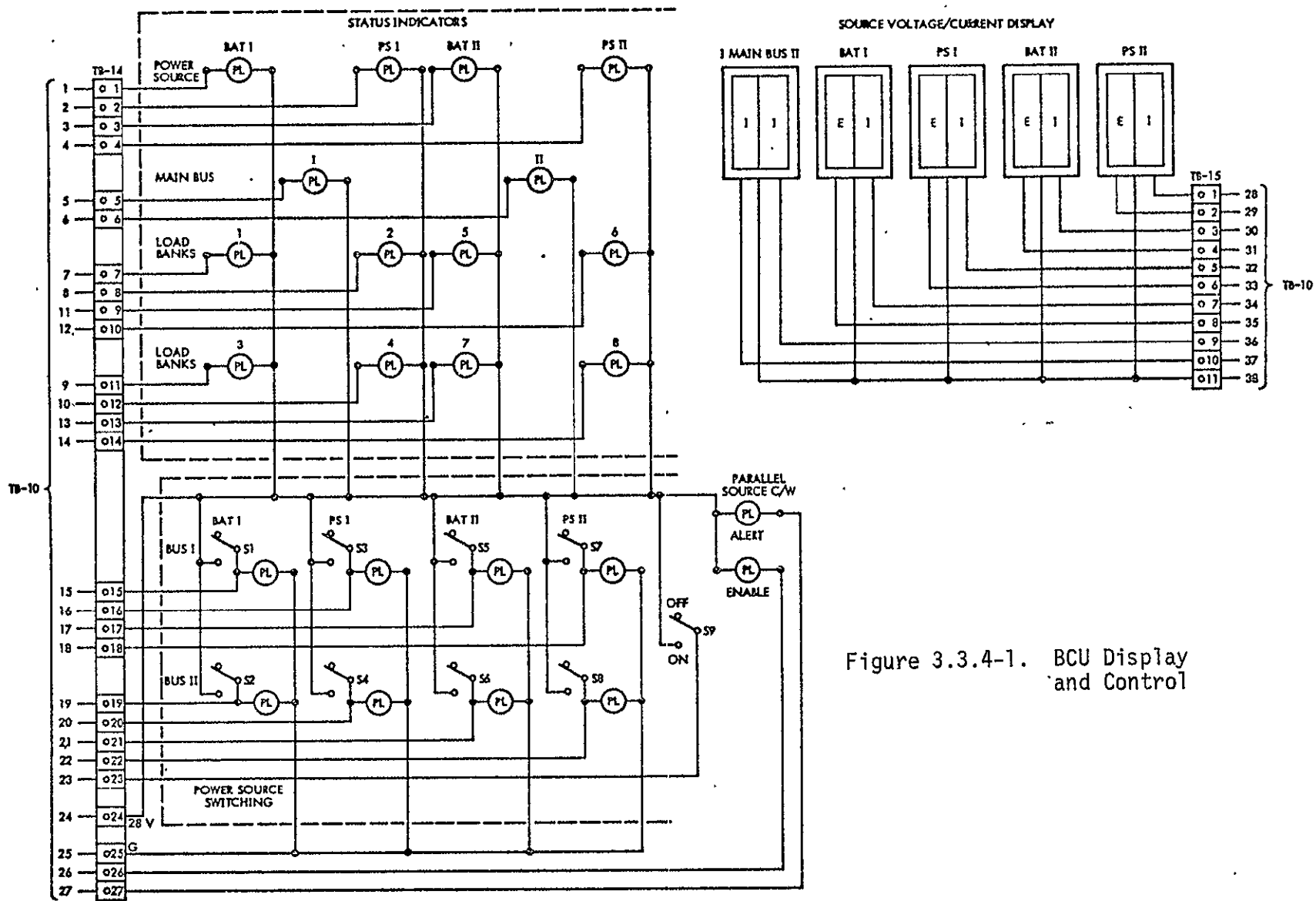


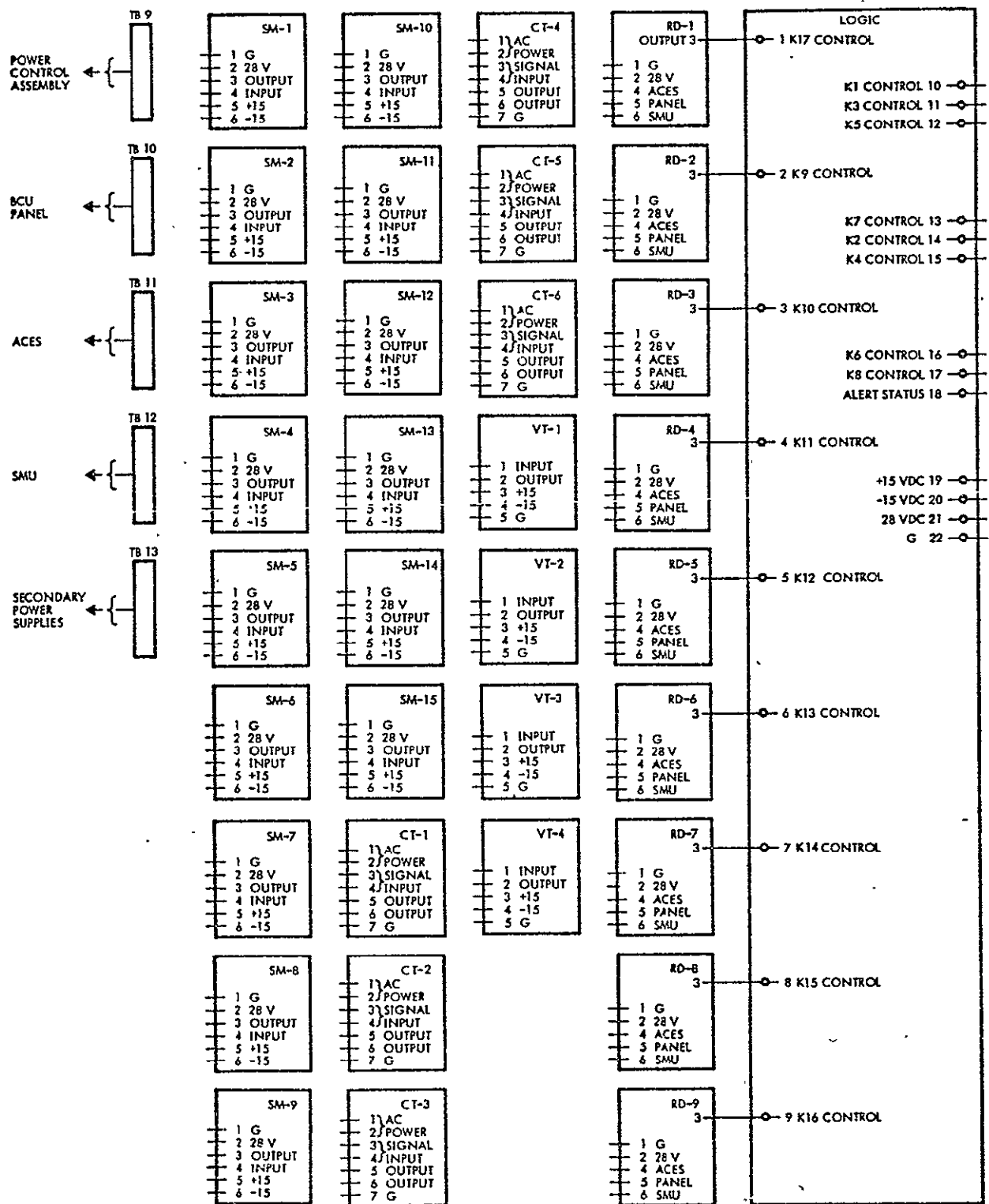
Figure 3.3.4-1. BCU Display and Control

"Parallel Alert" indication whenever two or more sources are interconnected. Since all power sources can be operated "ON" from any of three locations (BCU, SMU, ACES DED) caution must be observed in the operation of switch-gear from more than one panel. Panel lights are provided at each control station to indicate the "ON" state of a switch, but no safeguards are provided beyond these indicators and the inhibit/alert functions discussed above. More elaborate safety functions do not appear to have sufficient merit to be included in the design since the capability to interconnect power sources is necessary for some test operations. Ultimately, the avoidance of inadvertant power source interconnections must depend on the design of operational methods and procedures.

3.3.5 Signal Conditioning Electronics

The signal conditioning electronics (Figure 3.3.5-1) provides the interface between the power distribution system and the various controls and displays. The functions of this component include generation of bi-level status signals, voltage and current analog signals and logic for the power source contactor control. Figure 3.3.5-1 illustrates the type and multiplicity of signal conditioning elements. The requirement for compatibility between ACES, SMU and BCU controls and displays established the signal interface design. Although it has become standard to transmit bi-level signals across an interface by "open" or "closed" contacts (transistor cut-off or saturation), ACES implements controls by applying 28V in the "ON" condition and essentially zero volts in the "OFF". This design reflects the need to be able to sense the state of the switching function when the circuit to which the control function is applied is temporarily de-energized. Switching functions on the BCU and SMU panels are designed to be compatible with ACES and provide similar commands.

The interface characteristics of the ACES RIO and the signal conditioning electronics are detailed in Table 3.3.5-1. Status monitor and relay driver designs are similar to those used in the load bank. Circuit design details are provided in the following paragraphs.



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Figure 3.3.5-1. BCU Electronics

Table 3.3.5-1. ACES/BCU Control and Signal Interface

<u>ACES RIO</u>	<u>BCU SIGNAL CONDITIONING ELECTRONICS</u>
Control	Relay Driver
"ON"	
Open Circuit Voltage (L) $\leq 28V^*$	Maximum Input Voltage (P) $\leq 40V$
Maximum Load Current (P) $< 0.04A$	Maximum Input Current (L) @ 30V $< 0.006A$
"OFF"	
Maximum Output Current (L) $< 40\mu A$	Maximum Input Current (P) $< 200\mu A$
Status Sense	Status Output
Sense "ON"	Status = "ON"
Output Current (L) $2.7 \pm 20\%$ milliamps	Min. Sink Current (R) $\leq 100\text{ ma}$
Sense "OFF"	Status = "OFF"
Maximum Sink Current (P) $< 40\mu A$	Max Sink Current (L) < 0
Open Circuit Voltage $< 15V(L)$	Max Voltage $\leq 28V^*$
L = Circuit Limited	* Power Source Voltage
P = Permissible Limit	
R - Required Value	

The status monitors (indicated by SM- on Figure 3.3.5-1) are designed to indicate presence or absence of voltage and provide drive for two panel lamps. The circuit design for this function is shown in Figure 3.3.5-2. The maximum current through the 2N2222 for two panel lamps (40 ma per lamp) and the ACES logic input ($2.7\text{ ma} \pm 20\%$) is 83.2 ma. The integrated circuit IC-1 supplies 2.8 ma minimum base drive to Q1 to supply this load. IC-1 is a biased bi-stable circuit designed to operate "ON" with +20 volts at the input (terminal 4) and "OFF" with 14 volts at that terminal. This circuit was

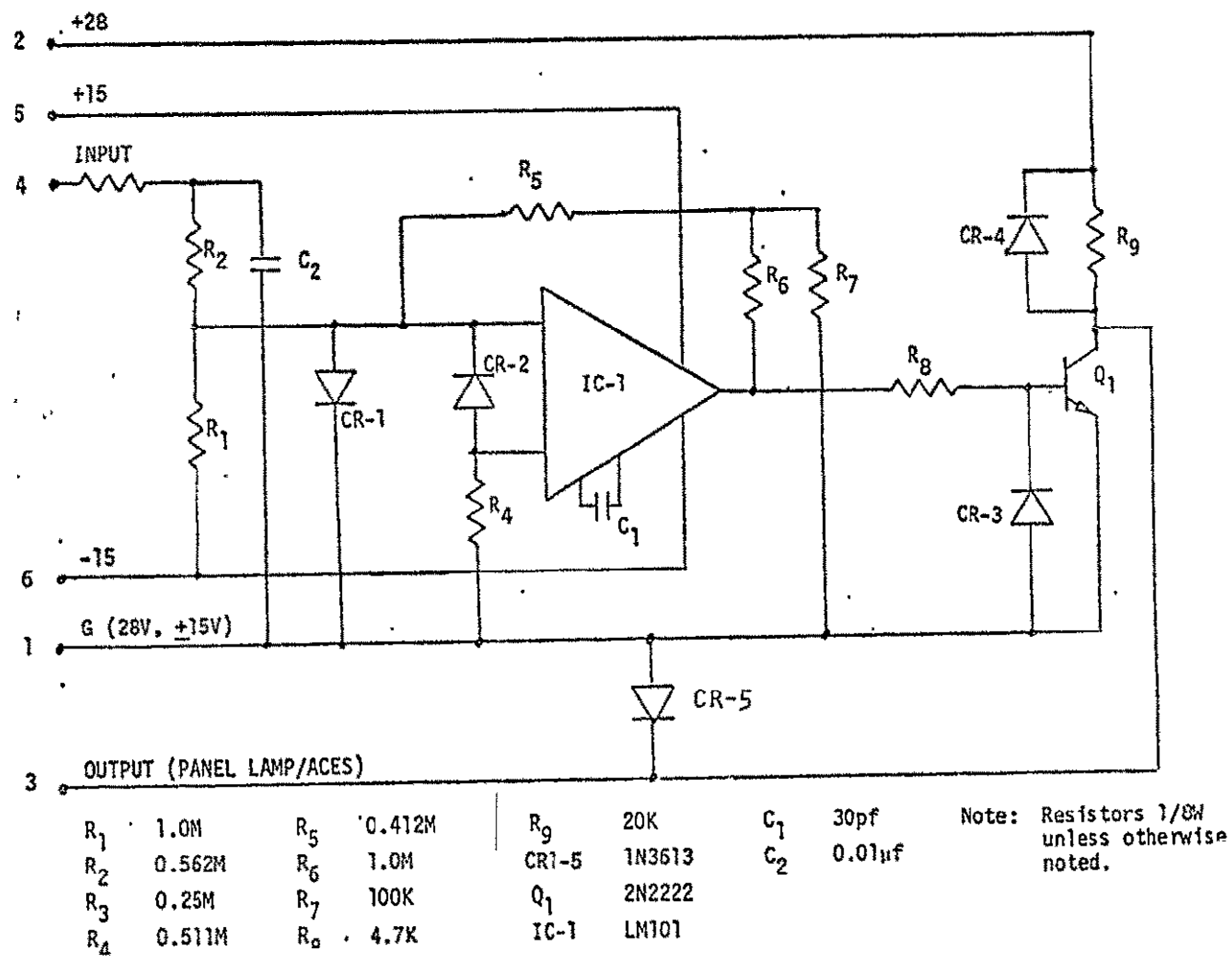


Figure 3.3.5-2. Status Sense Circuit

evaluated for worst case response with the ICAP program; parameters used in this analysis are given below.

Table 3.3.5-2. Worst Case Parameters

LM101	
Input Offset Voltage	± 5 mv
Input Offset Current	$200 \pm 10\%$ nA
Input Bias Current	$400 \pm 10\%$ nA
Input Resistance	300, 800 K ohms
Voltage Gain	25, 160 V/mV
All Resistors	$\pm 1\%$
All Voltages	$\pm 5\%$

The sensitivity of the input trigger levels was determined by adding a dummy high gain negative feedback loop between the output of IC-1 and terminal 4 of the input. Resistor R4 was lifted from the output of IC-1 and connected to ± 15 volts to simulate the two stable output states of the circuit. The input is then driven to the voltage which produces the transition state (zero volts) at the output of IC-1. This evaluation resulted in the following data.

Table 3.3.5-3. Status Monitor Worst Case

<u>Condition</u>	<u>Required Input Voltage</u>
ON	$17.69 < E < 21.06$ VDC
OFF	$14.89 > E > 11.65$

The significant values, minimum "ON" voltage and maximum "OFF" voltage indicate range of operation under worst case conditions. In an actual design the two trigger levels would tend to track and margins between levels will be approximately 6 volts.

The BCU current monitor circuits (CT- in Figure 3.3.5-1) are shown in Figure 3.3.5-3 for illustration purposes only. It is expected

that a purchased component will be more economical than in-house design. This design provides necessary isolation between the high voltage bus and the BCU electronics and is not subject to damage due to high current surges during fault condition.

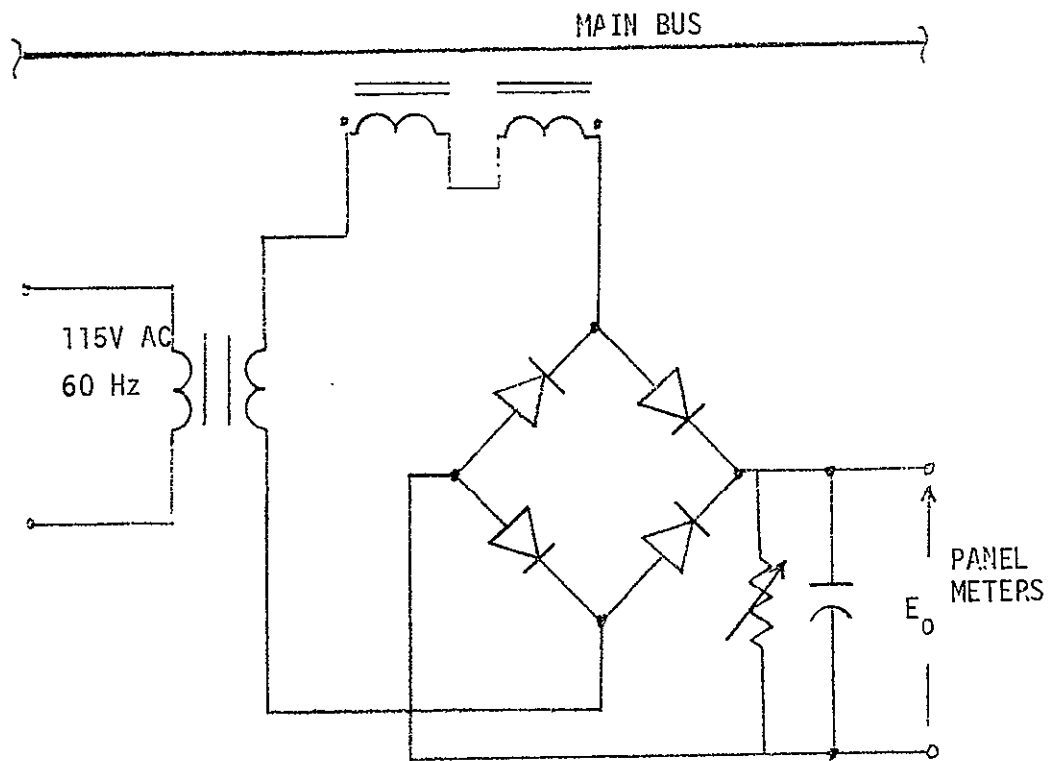
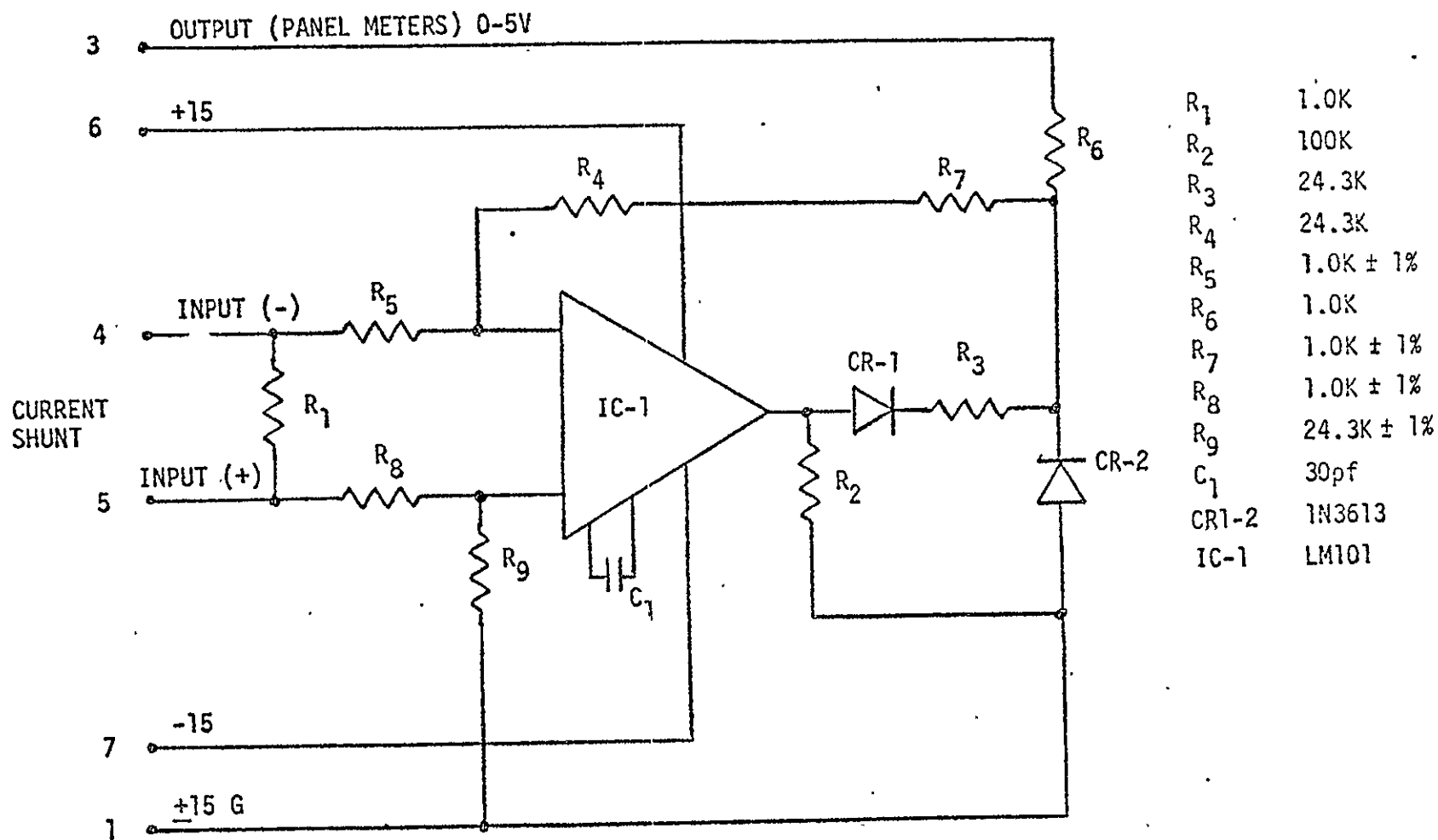


Figure 3.3.5-3. Magnetically Coupled Current Transducer

If this current should prove to be unacceptable due to cost (\$170 estimated) or physical incompatibility, the current monitor designed for the load bank may be used (Figure 3.3.5-4). This amplifier conditions voltage developed across a current shunt (0- 0.2VDC) to standard meter display drive voltage (0- 5.0VDC). Although the meters have not been selected for this program and will probably be obtained from MSFC storage, the design may be easily modified to any standard meter characteristic. Worst case operation of this amplifier was evaluated with parameter variation similar to those for the status monitor. Output voltage stability was evaluated for minimum and maximum input conditions and yielded the results below.



NOTE: All resistors 1/8 watt
unless otherwise noted.

Figure 3.3.5-4. Current Shunt Signal Conditioner

Table 3.3.5-4. Current Monitor - Worst Case

Input Voltage	Output Voltage (Volts)		
	MIN.	NOMINAL	MAX.
0	-0.149	-0.001	+0.143
0.2	4.829	5.072	5.323

Current shunts would be placed in the main bus and power source return at the single point ground in the secondary power distribution assembly (Figure 3.3.3-1). Since this adds contacts in series with the power circuits and will not register all main bus fault currents it is the less desirable approach but will perform adequately.

The relay drivers (RD- on Figure 3.3.5-1) consist of a straight-forward semiconductor switch as illustrated in Figure 3.3.5-5. Bi-level control signals are input at terminals 4, 5 and 6. The relay coils are connected between the 28V bus and terminal 3. The ACES RIO provides 28VDC in the "ON" condition and essentially zero in the "OFF" condition. ACES commanded characteristics are given in Table 3.3.5-5.

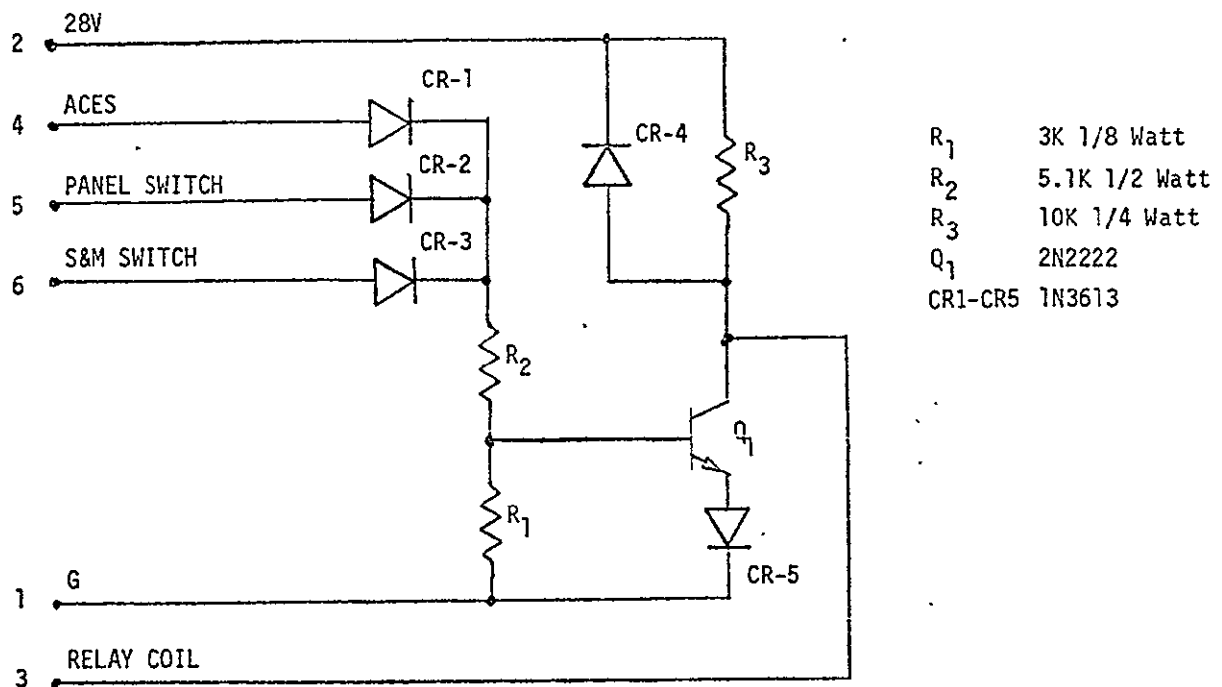


Figure 3.3.5-5. Relay Drive Circuit

Table 3.3.5-5. ACES Command Interface

CONDITION	
"ON"	Source Voltage 28VDC \pm 10%
	Source Impedance 100 Ω
	Maximum Current <0.04 Amperes
"OFF"	Maximum Current <40 Microamperes

The panel switches on the BCU and SMU panels provide 28VDC from secondary power bus in the "ON" condition and open circuit in the "OFF" condition. With these input conditions it appears unnecessary to define more elaborate circuitry for this function. The relay driver responds to any of the three inputs on a logical "OR" basis for the "ON" condition and a logical "AND" basis for the "OFF" condition. Consequently, supervision panels which are not functioning should have all control switches in the "OFF" position. The design assumes a worst case Beta of 30 for the 2N2222 which is adequate for laboratory operation.

Voltage conditioning circuits (VT- on Figure 3.3.5-1) are designed to provide 0-5V output for inputs of 0-300V with an output impedance of approximately 1.0K Ω (Figure 3.3.5-6). Expected variation of output signal is less than 3% with time and temperature. If R1, R6, R3 and R4 are 1% tolerance, zero set adjustment (R6) will not be required. Simple voltage dividers (eight) may be substituted for the signal conditioning circuit if compatible panel meters can be obtained.

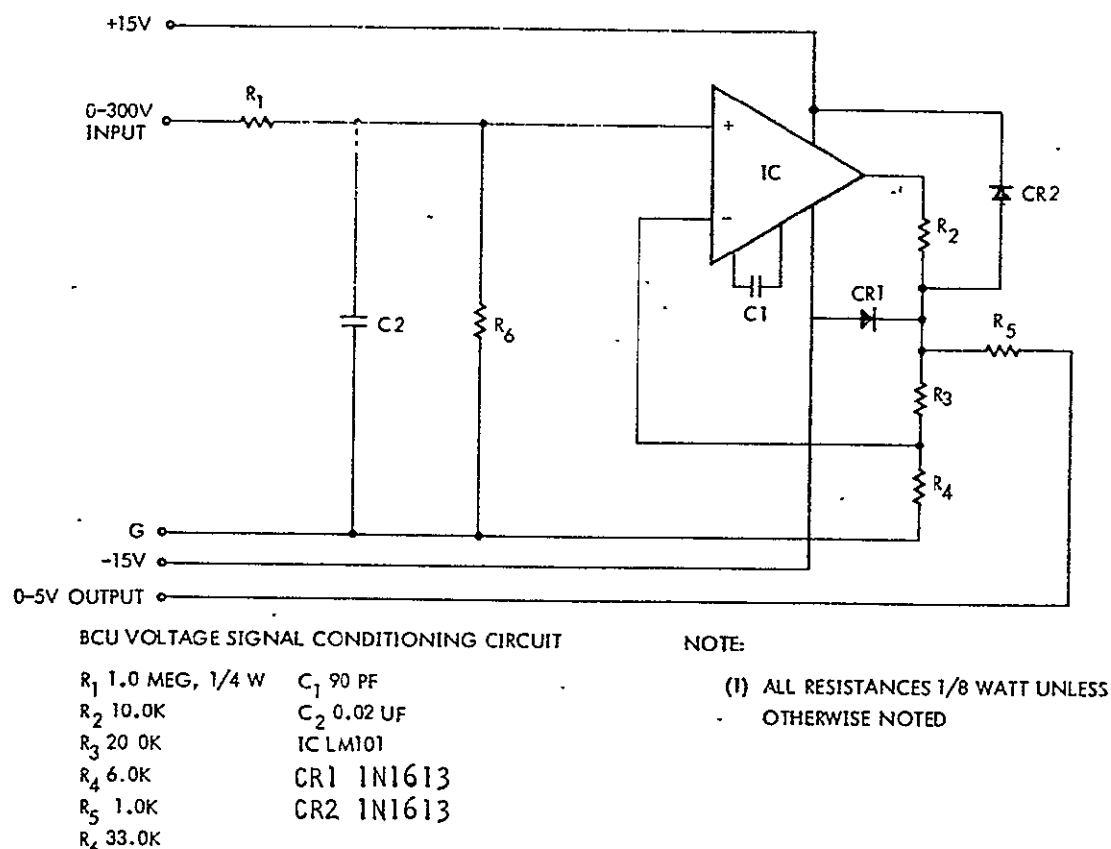


Figure 3.3.5-6. Voltage Measurement Transducer

The signal conditioning logic circuitry is illustrated in Figure 3.3.5-7. Switch assembly contactors K1, K3, K5 and K7 are energized through the normally open contacts of relays K9, K10, K11 and K12 respectively. Each relay in this group of four is energized through the normally closed contacts of the other three relays in the group. Operation of any one relay inhibits subsequent operation of another relay in the group. Since the above contactors all connect a power source to the bus (i.e., main bus 2), the connection of more than one contactor to a bus is inhibited. An attempt to operate a second relay in the group when this inhibit condition exists will result in increased voltage drop across R1 due to current through the diode (CR1-CR4) connected to the second relay selected. The increased voltage drop across R1 will cause the output of IC-1 to go positive and activate the parallel alert indicator on the display panels.

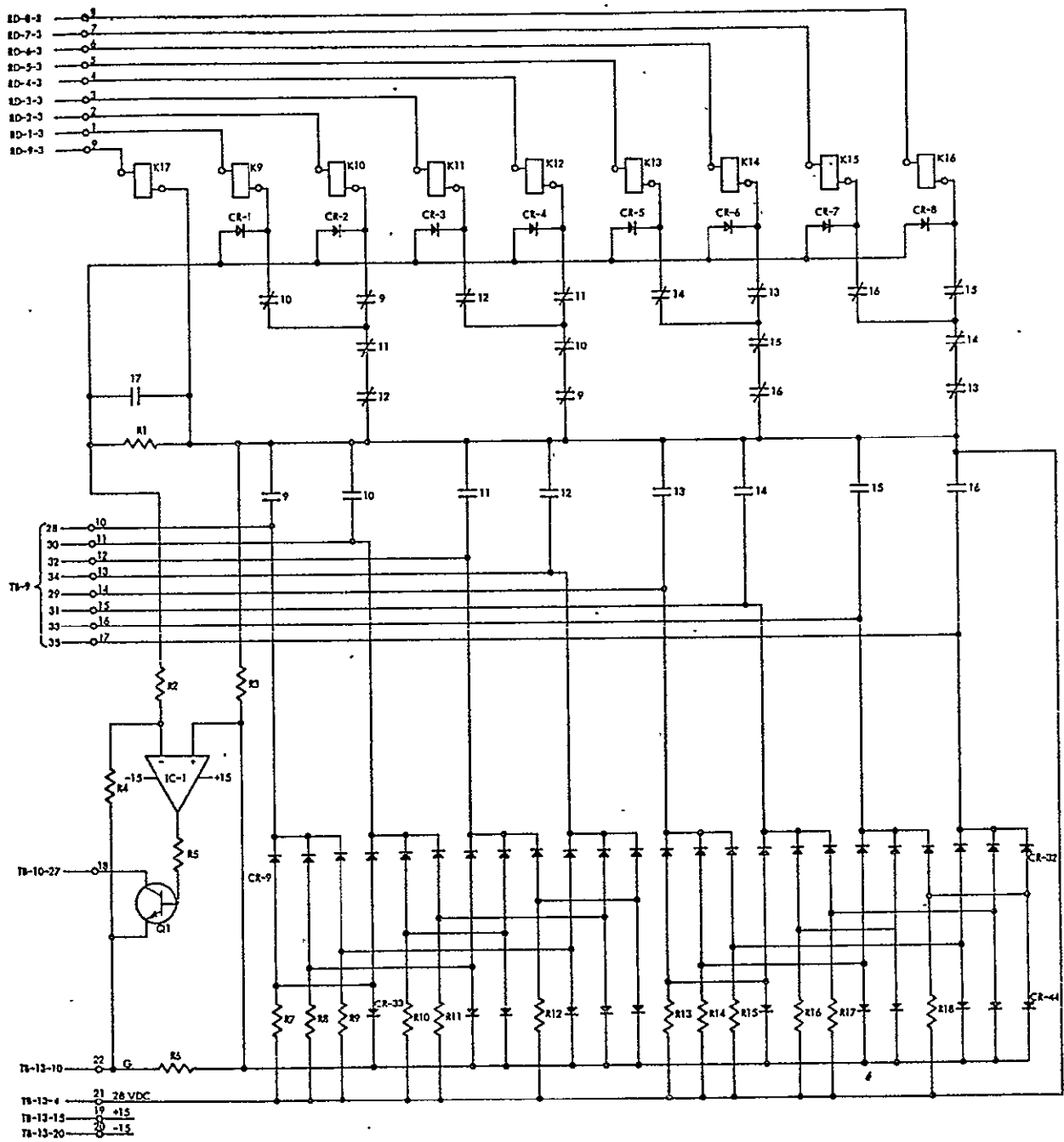


Figure 3.3.5-7. BCU Contactor Control Logic

Operation of the parallel enable switch on the BCU panel closes the contacts of K17 bypassing the normally closed contacts in relay groups and permitting all relays to be energized through diodes CR1-CR4. Subsequent operation of two or more relays in this group will cause the voltage at output of the diode logic (CR33-CR38) to rise resulting in increased voltage at the input (+) terminal of IC-1 and activation of the parallel alert indicator on the display panels.

The status signal for the parallel source enable indicator is obtained from the relay driver (RD-1-7) for K17. This indicator is energized on all displays regardless of which control panel initiates the command. It should be noted that this indicator responds to the presence of command rather than execution to minimize the potential for creating a hazardous condition due to single part failure.

3.3.6 Interfaces

The wiring interfaces between BCU components are listed in Tables 3.3.6-1 to Table 3.3.6-5. Connections within the components are illustrated on the drawings. Updated cable lists between the BCU and other subsystems are given in Tables 3.3.6-6 to Table 3.3.6-15. Additional details on cables and connectors may be obtained from the May 1975 report on this contract.

Table 3.3.6-1. BCU Signal Conditioning Electronics Interface

SIGNAL	INTERFACE		ELECTRONICS		
	TERMINAL BOARD	TERMINAL	TERMINAL BOARD	TERMINAL	ELECTRONICS TERMINAL
Bat 1 Status	14 (BCU Panel)	1	10	1	SM-1-3, TB-12-1
PS 1 Status	14	2	10	2	SM-2-3, TB-12-2
Bat 2 Status	14	3	10	3	SM-3-3, TB-12-3
PS 2 Status	14	4	10	4	SM-4-3, TB-12-4
Main Bus 1 Status	14	5	10	5	SM-5-3, TB-12-5
Main Bus 2 Status	14	6	10	6	SM-6-3, TB-12-6
Load Bus 1 Status	14	7	10	7	SM-7-3, TB-12-7
Load Bus 2 Status	14	8	10	8	SM-8-3, TB-12-8
Load Bus 3 Status	14	9	10	9	SM-9-3, TB-12-9
Load Bus 4 Status	14	10	10	10	SM-10-3, TB-12-10
Load Bus 5 Status	14	11	10	11	SM-11-3, TB-12-11
Load Bus 6 Status	14	12	10	12	SM-12-3, TB-12-12
Load Bus 7 Status	14	13	10	13	SM-13-3, TB-12-13
Load Bus 8 Status	14	14	10	14	SM-14-3, TB-12-14
Bat 1/Bus 1 SW	14	15	10	15	RD-2-5
PS 1/Bus 1 SW	14	16	10	16	RD-3-5
Bat 2/Bus 1 SW	14	17	10	17	RD-4-5
PS 2/Bus 1 SW	14	18	10	18	RD-5-5
Bat 1/Bus 2 SW	14	19	10	19	RD-6-5
PS 1/Bus 2 SW	14	20	10	20	RD-7-5
Bat 2/Bus 2 SW	14	21	10	21	RD-8-5
PS 2/Bus 2 SW	14	22	10	22	RD-9-5
Parallel Source SW	14	23	10	23	RD-1-5
28V DC	14	24	10	24	TB-13-3
Ground	14	25	10	25	TB-13-12, TB-10-37
Parallel Source Enable	14	26	10	26	SM-15-3, TB-12-16
Parallel Source Alert	14	27	10	27	Logic-18, TB-12-15
I Display PS 2	15 (BCU Panel)	1	10	28	CT-4-5
E Display PS 2	15	2	10	29	VT-4-2, TB-12-25
I Display Bat 2	15	3	10	30	CT-3-5
E Display Bat 2	15	4	10	31	VT-3-2, TB-12-26
I Display PS 1	15	5	10	32	CT-2-5
E Display PS 1	15	6	10	33	VT-2-2, TB-12-23
I Display Bat 1	15	7	10	34	CT-1-5
E Display Bat 1	15	8	10	35	VT-1-2, TB-12-24
I Display Main Bus 2	15	9	10	36	CT-6-5
E Display Main Bus 2	15	10	10	37	CT-5-5
Ground	15	11	10	38	TB-10-25

Table 3.3.6-2. BCU Signal Conditioning Electronics Interface

SIGNAL	INTERFACE		ELECTRONICS		
	TERMINAL BOARD	TERMINAL	TERMINAL BOARD	TERMINAL	ELECTRONICS TERMINAL
Bat 1 Status	16 (Aces Rio)	1	11	1	TB-12-1
PS 1 Status		2		2	TB-12-2
Bat 2 Status		3		3	TB-12-3
PS 2 Status		4		4	TB-12-4
Main Bus 1 Status		5		5	TB-12-5
Main Bus 2 Status		6		6	TB-12-6
Load Bus 1 Status		7		7	TB-12-7
Load Bus 2 Status		8		8	TB-12-8
Load Bus 3 Status		9		9	TB-12-9
Load Bus 4 Status		10		10	TB-12-10
Load Bus 5 Status		11		11	TB-12-11
Load Bus 6 Status		12		12	TB-12-12
Load Bus 7 Status		13		13	TB-12-13
Load Bus 8 Status		14		14	TB-12-14
Parallel Source Enable		15		15	TB-12-15
Parallel Source Alert	16	16	11	16	TB-12-16
Bat 1/Bus 1 SW	16	21	11	21	RD-2-4
PS 1/Bus 1 SW		22		22	RD-3-4
Bat 2/Bus 1 SW		23		23	RD-4-4
PS 2/Bus 1 SW		24		24	RD-5-4
Bat 1/Bus 2 SW		25		25	RD-6-4
PS 1/Bus 2 SW		26		26	RD-7-4
Bat 2/Bus 2 SW		27		27	RD-8-4
PS 2/Bus 2 SW		28		28	RD-9-4
Parallel Source SW	16	29	11	29	RD-1-4

Table 3.3.6-3. BCU Signal Conditioning Electronics Interface

SIGNAL	INTERFACE			ELECTRONICS	
	CONNECTOR	TERMINAL	TERMINAL BOARD	TERMINAL	ELECTRONICS TERMINAL
PS 1 Status	J4	1	12	1	TB-10-1, TB-11-1
Bat 1 Status	J4	2	12	2	TB-10-2, TB-11-2
PS 2 Status	J4	3	12	3	TB-10-3, TB-11-3
Bat 2 Status	J4	4	12	4	TB-10-4, TB-11-4
Main Bus 1 Status	J4	5	12	5	TB-10-5, TB-11-5
Main Bus 2 Status	J4	6	12	6	TB-10-6, TB-11-6
Load Bus 1 Status	J4	7	12	7	TB-10-7, TB-11-7
Load Bus 2 Status	J4	8	12	8	TB-10-8, TB-11-8
Load Bus 3 Status	J4	9	12	9	TB-10-9, TB-11-9
Load Bus 4 Status	J4	10	12	10	TB-10-10, TB-11-10
Load Bus 5 Status	J4	11	12	11	TB-10-11, TB-11-11
Load Bus 6 Status	J4	12	12	12	TB-10-12, TB-11-12
Load Bus 7 Status	J4	13	12	13	TB-10-13, TB-11-13
Load Bus 8 Status	J4	14	12	14	TB-10-14, TB-11-14
Parallel Alert	J4	15	12	15	TB-10-27, TB-11-16 Alert
Parallel Active	J4	16	12	16	TB-10-26, TB-11-15 Active
Current PS 1	J4	17	12	17	CT-2-6
Current Bat 1	J4	18	12	18	CT-1-6
Current PS 2	J4	19	12	19	CT-4-6
Current Bat 2	J4	20	12	20	CT-3-6
Current Main Bus 1	J4	21	12	21	CT-5-6
Current Main Bus 2	J4	22	12	22	CT-6-5
Voltage PS 1	J4	23	12	23	TB-10-33
Voltage Bat 1	J4	24	12	24	TB-10-35
Voltage PS 2	J4	25	12	25	TB-10-29
Voltage Bat 2	J4	26	12	26	TB-10-31
Bat 1/Main Bus 1 SW	J4	27	12	27	RD-2-
PS 1/Main Bus 1 SW	J4	28	12	28	RD-3-6
Bat 2/Main Bus 1 SW	J4	29	12	29	RD-4-6
PS 2/Main Bus 1 SW	J4	30	12	30	RD-5-6
Bat 1/Main Bus 2 SW	J4	31	12	31	RD-6-6
PS 1/Main Bus 2 SW	J4	32	12	32	RD-7-6
Bat 2/Main Bus 2 SW	J4	33	12	33	RD-8-6
PS 2/Main Bus 2 SW	J4	34	12	34	RD-9-6
Parallel Source SW	J4	35	12	35	RD-1-6
28V Power	J4	36	12	36	TB-13-1, SM-1-2 through SM-15-2
120V G	J4	37	12	37	TB-13-26
Signal G	J4	38	12	38	TB-13-11, SM-1-1 through SM-15-1

Table 3.3.6-4. BCU Signal Conditioning Electronics Interface

SIGNAL	INTERFACE		ELECTRONICS			
	TERMINAL BOARD	TERMINAL	TERMINAL BOARD	TERMINAL	ELECTRONICS	TERMINAL
28V DC	19	9	13	1	TB-12-36, TB-13-2	
			13	2	TB-13-1, TB-13-3, RD-1-2 thru RD-9-2	
			13	3	TB-13-2, TB-13-5, TB-10-24	
			13	4	TB-13-3, Logic-21	
			13	5		
			13	6		
			13	7	TB-13-8, VT-1-5 through VT-4-5	
			13	8	TB-13-7, TB-13-9, CT-1-7 thru CT-6-7	
			13	9	TB-13-8, TB-13-10, RD-1-1 thru RD-9-1	
			13	10	TB-13-9, TB-13-11, Logic-22	
Secondary Power G	19	22	13	11	TB-13-10, TB-13-12, TB-12-38	
			13	12	TB-13-11, TB-13-13, TB-10-25	
			13	13	TB-13-12	
			13	12		
			13	13	TB-13-14, SM-1-5 through S-15-5	
			13	14	TB-13-13, TB-13-15, VT-1-3, thru VT-4-3	
			13	15	TB-13-14, TB-13-16, Logic-19	
			13	16	TB-13-15	
			13	17		
			13	18	TB-13-19, SM-1-6, through SM-15-6	
+15V DC	19	10	13	19	TB-13-18, TB-13-20, VT-1-4 thru VT-4-4	
			13	20	TB-13-19, TB-13-21, Logic-20	
-15V DC	19	11	13	21	TB-13-20	
			13	22		
115V AC-2	20	3	13	23	CT-1-1 thru CT-6-1	
115V AC-1	20	6	13	24	CT-1-2 thru CT-6-2	
Single Point G	TS1		13	25		
			13	26	TB-12-37	

Table 3.3.6-5. BCU Signal Conditioning Electronics Interface

SIGNAL	INTERFACE		ELECTRONICS		
	TERMINAL BOARD	TERMINAL	TERMINAL BOARD	TERMINAL	ELECTRONICS TERMINAL
Bat 1 Status/Voltage	6	1	9	1	SM-1-4, VT-1-1
PS 1 Status/Voltage	6	2	9	2	SM-2-4, VT-2-1
Bat 2 Status/Voltage	6	3	9	3	SM-3-4, VT-3-1
PS 2 Status/Voltage	6	4	9	4	SM-4-4, VT-4-1
Bat 1 Current A	6	5	9	15	CT-1-1
Bat 1 Current B	6	6	9	16	CT-1-2
PS 1 Current A	6	7	9	17	CT-2-1
PS 1 Current B	6	8	9	18	CT-2-2
Bat 2 Current A	6	9	9	19	CT-3-1
Bat 2 Current B	6	10	9	20	CT-3-2
PS 2 Current A	6	11	9	21	CT-4-1
PS 2 Current B	6	12	9	22	CT-4-2
Main Bus 1 Current A	7	1	9	23	CT-5-1
Main Bus 1 Current B	7	2	9	24	CT-5-2
Main Bus 2 Current A	7	3	9	25	CT-6-1
Main Bus 2 Current B	7	4	9	26	CT-6-2
Contractor Control G	6	13	9	27	
K1 Control	6	14	9	28	Logic-10
K2 Control	6	15	9	29	Logic-14
K3 Control	6	16	9	30	Logic-11
K4 Control	6	17	9	31	Logic-15
K5 Control	6	18	9	32	Logic-12
K6 Control	6	19	9	33	Logic-16
K7 Control	6	20	9	34	Logic-13
K8 Control	6	21	9	35	Logic-17
Main Bus 1 Status	7	5	9	5	SM-5-4
Main Bus 2 Status	7	6	9	6	SM-6-4
Load Bus 1 Status	8	1	9	7	SM-7-4
Load Bus 2 Status	8	2	9	8	SM-8-4
Load Bus 3 Status	8	3	9	9	SM-9-4
Load Bus 4 Status	8	4	9	10	SM-10-4
Load Bus 5 Status	8	5	9	11	SM-11-4
Load Bus 6 Status	8	6	9	12	SM-12-4
Load Bus 7 Status	8	7	9	13	SM-13-4
Load Bus 8 Status	8	8	9	14	SM-14-4

Table 3.3.6-6. Cable Identification

<u>Cable Harness & Wiring</u>	
<u>Cable</u>	<u>Description</u>
WP1-()	Main bus power distribution, BCU to Load Banks ()
WP2-()	Secondary power (28VDC) dist., BCU to Load Banks ()
WP3	Source Power distribution, Battery I to BCU
WP4	Source power distribution, power supply I to BCU
WP5	Source power distribution, Battery II to BCU
WP6	Source power distribution, power supply II to BCU
WS1-()	Control and monitor signals, SMU to Load Bank ()
WS2-()	Control and monitor signals, ACES to Load Banks
WS3	Control and monitor signals, SMU to BCU
WS4	Control and monitor signals, ACES to BCU

Table 3.3.6-7. Wire List

BCU	COMPONENT - CABLE # WP1-()					LOAD BANK
Connector Terminal Lugs TB5-() Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs TB1-() Terminal
1	8	20	300	DC	Load Bus-Power	1
2						2
3						3
4						4
5			300		Load Bus-Power	5
6			-		Load Bus-Power	6
7			-		Return	7
8			-			8
9			-			9
10	8	20	-	DC	Load Bus-Power Return	10

Table 3.3.6-8. Wire List

BCU	COMPONENT - CABLE # WP2-()					LOAD BANK
Connector Terminal Lugs P3-() Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs P5-() Terminal
1	12	4	28	DC	28 VDC Power	1
2	12	4	-	DC	28 VDC Ret	2
3	12	-	-	Spare	-	3
4	12	-	-	Spare	-	4

Table 3.3.6-9. Wire List

BAT I	COMPONENT CABLE # WP3					BCU
Connector Terminal Lugs TB1 Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs TB1 Terminal
1	00	150	120	DC	120 VDC Power	1
2	00	150	120	DC	120 VDC Return Frame G	2

Table 3.3.6-10. Wire List

POWER SUPPLY I	COMPONENT CABLE # WP4					BCU
Connector Terminal Lugs TB1 Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs TB2 Terminal
1	00	150	120	DC	120 VDC Power	1
2	00	150	120	DC	120 VDC Return	2
3	12	-	-	-	Frame G	3

Table 3.3.6-11. Wire List

BAT II	COMPONENT CABLE # WP5					BCU
Connector Terminal Lugs TB1 Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs TB3 Terminal
1	00	150	120	DC	120 VDC Power	1
2	00	150	120	I	120 VDC Return	2
3	12	-	-	-	Spare	3

Table 3.3.6-12. Wire List

POWER SUPPLY II	COMPONENT CABLE # WP6					BCU
Connector Terminal Lugs TB1 Terminal	AWG Guage	Current Amps	Voltage Volts	Signal	Function	Connector Terminal Lugs TB4 Terminal
1	00	150	120	DC	120 VDC Power	1
2	00	150	120	DC	120 VDC Return	2
3	12	-	-	-	Frame G	3

Table 3.3.6-13. Wire List

ACES	COMPONENT - CABLE # WS2-()	LOAD BANK
Connector Terminal		Connector Terminal
Cable and connector design specified in ACES Manual - see Westinghouse Dwg. No. 361332		

Table 3.3.6-14. Wire List

BCU		COMPONENT - CABLE IDENT # WS3				SMU	
Connector P4 Terminal	AWG Gauge	Current Amps	Voltage Volts	Signal Type	Function	Connector P2 Terminal	
1	22	0.04	28	Bi-level	Status PS-1	1	
2					BAT-1	2	
3					PS-2	3	
4					BAT-2	4	
5					Main Bus 1	5	
6					Main Bus 2	6	
7					Load Bus 1	7	
8					Load Bus 2	8	
9					Load Bus 3	9	
10					Load Bus 4	10	
11					Load Bus 5	11	
12					Load Bus 6	12	
13					Load Bus 7	13	
14					Load Bus 8	14	
15					Parallel Alert	15	
16	22	0.04	28	Bi-level	Status Parallel Active	16	
17	22	<0.01	28	Analog	Meas Current PS-1	17	
18	22	<0.01	28	Analog	Current BAT-1	18	
19					Current PS-2	19	
20					Current BAT-2	20	
21					Current Main Bus 1	21	
22					Current Main Bus 2	22	
23					Voltage PS-1	23	
24					Voltage BAT-1	24	
25					Voltage PS-2	25	
26	22	<0.01	28	Analog	Meas Voltage BAT-2	26	
27	22	<0.01	28	Bi-level	Command BAT-1 Main Bus 1	27	
28	22	<0.01	28	Bi-level	PS-1/Main Bus 1	28	
29					BAT-2/Main Bus 1	29	
30					PS-2/Main Bus 1	30	
31					BAT-1/Main Bus 2	31	
32					PS-1/Main Bus 2	32	
33	22	<0.01	28	Bi-level	Command PS-2/Main Bus 2	33	
34	22	0.04	28	Bi-level	Command Parallel Source	34	
35	22	2.0	28	DC	28 V Power	35	
36	22	2.0	-	DC	120 V Grnd	36	
37	22	-	-	-	Signal Grnd	37	
38	22	-	-	-	Spare	38	
39	22					39	
40						40	
41						41	
42						42	
43						43	
44						44	
45						45	
46						46	
47						47	
48						48	
49						49	
50						Spare	50

Table 3.3.6-15. Wire List

ACES	COMPONENT - CABLE # WS4	ACU BANK
Connector Terminal		Connector Terminal
Cable and Connector design specified in ACES manual - see Westinghouse Dwg. No. ED361332		